TECHNICAL REPORT NO. 11108 (LL 140)

ANALYTICAL PREDICTION OF VEHICLE MOBILITY ON MUSKEG

U.S. ARMY TANK AUTOMOTIVE COMMAND
LABORATORIES

Final Report
June 1970

by
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Keweenaw Research Center
Michigan Technological University
DA-20-018-AMC-0989(T)

TACOM

MOBILITY SYSTEMS LABORATORY

U.S. ARMY TANK AUTOMOTIVE COMMAND Warren, Michigan

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92

Unclassified
Security Classification

DOCUMENT CONTROL DATA - R & D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY (Corporate author) Keweenaw Research Center Michigan Technological University Houghton, Michigan	2a. REPORT SECURITY CLASSIFICATION Unclassified 2b. GROUP N/A

3. REPORT TITLE
Analytical Prediction of Vehicle Mobility on Muskeg.

4. DESCRIPTIVE NOTES (Type of report and inclusive dates) Final Report

5. AUTHOR(S) (First name, middle initial, last name)
Ed W. Niemi
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6. REPORT DATE June 1970	7a. TOTAL NO. OF PAGES 99	7b. NO. OF REFS 4
8a. CONTRACT OR GRANT NO. DA-20-018-AMC-0989(T) new b. PROJECT NO. c. d.	9a. ORIGINATOR'S REPORT NUMBER(S) 11108 9b. OTHER REPORT NO(S) (Any other numbers that may be assigned this report) LL 140	

10. DISTRIBUTION STATEMENT
Distribution of this report is unlimited.

11. SUPPLEMENTARY NOTES	12. SPONSORING MILITARY ACTIVITY U. S. Army Tank-Automotive Command MobilitySystems Laboratory Vehicle Locomotion Section

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Two lightweight, low ground pressure tracked vehicles, M29C Weasel and Spryte 1301, were used in the verification tests. Towing tests were conducted at various speeds and the minimum resistance was found at 3 mph ground speed. Drawbar-pull tests resulted in maximum net tractive effort being generated at 25% slip. The results of these tests indicate that a large perimeter to area ratio on tracked vehicles is required for maximum mobility over muskeg.

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DD FORM 1 NOV 65 1473 REPLACES DD FORM 1473, 1 JAN 64, WHICH IS OBSOLETE FOR ARMY USE.

Unclassified
Security Classification

14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Muskeg						
Mobility						
Trafficability						
Peat						
Organic Terrain						
Drawbar tests						

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Vehicle Locomotion Projects
Surface Mobility Division
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ACKNOWLEDGEMENT

The helpful cooperation and suggestions received from Mr. R. A. Liston, Mr. L. A. Martin and the staff of the Vehicle Locomotion Projects office (USATACOM) are gratefully acknowledged.

The writers also wish to acknowledge the contributions of Dr. W. M. Haas of the MTU Civil Engineering Department and Mr. Ralph Hodek and Mr. Bruce Lanuni, Graduate Assistants, who were involved in the early phases of the project.

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INTRODUCTION

Mobility of vehicles over various kinds of terrain has been investigated by the military for many years. Qualitative performance, or mobility, has been measured by full-scale vehicle tests under various terrain conditions, a costly and time consuming process, frought with subjective judgement. Over the years, research in this area has been conducted by a number of investigators, and out of this effort has evolved a number of analytical techniques for predicting vehicle mobility; in some cases requiring only conceptual knowledge of the proposed vehicle. This has been done for both tracked and wheeled vehicles, and to some extent vehicles whose ground contact is through other devices.

The ability of a vehicle and terrain to interact has been evaluated analytically and theoretically from two vantage points. The physical capability of a vehicle to negotiate various types of terrain is frequently referred to as "mobility," a characteristic attributed to the vehicle; and the capacity of a given soil or terrain to withstand the travel of vehicles over it is frequently referred to as "trafficability," a characteristic attributed to the soil.

The terms "mobility" and "trafficability" are generally interpreted as separate and distinct characteristics of two different systems, namely the vehicle and the terrain. However, there is disagreement as to the acceptability and applicability of these terms, or even that they are meaningful concepts which can be evaluated quantitatively.

Soil characteristics have been investigated extensively both insitu and in the laboratory, and a variety of soil measuring instruments have been developed. Some of these are relatively simple, easily carried into the field, and the technique for using them can be readily acquired. Others are more complex and require auxiliary instrumentation. They also require considerably more operator skill to obtain the experimental data and to reduce these to a suitable quantitative form. The relative merits of the data obtained by the various methods are still subject to considerable debate.

The soil properties measured by the various sensing devices are considered to be characteristics which are independent of the interaction between the soil and a vehicle, and therefore characteristics of the soil, per se. These are generally termed "soil values." In many of the soil measuring devices, however, the sensing elements tend to simulate the action of a vehicle on the soil, and for this reason are considered to measure soil

characteristics that are relevant to vehicle travel over it. Thus the variables which determine vehicle mobility on a particular soil and its trafficability are, at least to some degree, manifestations of the same interacting factors.

The various methods of measuring soil values have been widely applied to most mineral soils, but only to a limited extent on organic soils, particularly muskeg terrain. The objective of this project was to investigate the properties of muskeg, to develop techniques for measuring those properties that are considered pertinent to vehicle mobility, and to develop an analytical method for predicting vehicle mobility in muskeg soil, using the soil values obtained.

MUSKEG, AN ORGANIC TERRAIN

Although muskeg is not a prominent terrain type in the United States it is quite significant in Canada and the northern European countries. Surveys have established that approximately one-eighth of the land area of Canada is organic terrain, representing nearly one-half million square miles. In the United States, muskeg occurs primarily in the northern fringe areas and largely as "confined" muskeg, although there are some fairly large areas in the Upper Peninsula of Michigan.

DEFINITION OF MUSKEG

The term muskeg is applied to organic terrain which consists of two physical strata— an upper layer of living vegetal cover, frequently referred to as the "mat," and a sublayer of peat. Underlying the peat is a mineral soil or rock. The overall depth of the muskeg may vary from a few feet up to more than 30 feet.

Muskeg areas vary in size from small pockets of "confined" muskeg to extremely large areas. The smaller, confined areas, tend to show considerable variation in physical characteristics, while the large, or unconfined, muskeg areas tend to be more uniform.

The living cover on muskeg areas may vary both in botanical type and growing height. Likewise the underlayer of peat may vary from amorphous-granular to coarse woody-fibrous, and in moisture content from less than 200 per cent up to 1500 per cent or more. In addition, the surface topographic features may vary from fairly uniform to quite irregular and hummocky.

MUSKEG CLASSIFICATION SYSTEM

Muskeg classification systems have been proposed by several investigators, with no one system being accepted universally. Since muskeg is an organic terrain, understandably most of the classification systems are based on the botanical classification of the living cover. In addition to classification according to the cover type, a further classification of muskeg is based on the physical aspects of the peat. Topographic features of the muskeg are used as an additional basis for classification.

The most widely used classification system in Canada is the Radforth Classification System,[4] first proposed by Dr. N. W. Radforth in 1952. This system will be used in this report.

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[4]Technical Memorandum 44, National Research Council, Canada, Guide to a Field Description of Muskeg, Compiled by I. C. MacFarlane, June, 1958.

In the Radforth System the living vegetal cover is designated by a combination of capital letters, with each letter representing a particular botanical group and the letters listed in order of prominence of the particular group. A particular classification may have one, two, or three letters, each designating a coverage type. To receive recognition a particular botanical group must cover more than 25 per cent of the area being classified.

The letters A, B, D, and E designate woody coverage types ranging downward from trees over 15 feet (A) to bushes 5 to 15 feet (B), to shrubs 2 to 5 feet (D), and to low shrubs 0 to 2 feet (E). The letters C, F, G, H, and I are used to designate non-woody growth, varying in types and ranging in heights up to 5 feet. The letter I designates mosses.[5]

The peat classification is divided into sixteen categories ranging from amorphous-granular (category 1) to woody coarse-fibrous (category 16). Topographical features are designated by lower case letters ranging from "a" to "p," with each letter designating a particular topographical formation.

In that the botanical types of living cover are most readily observed, this facet of the Radforth System is most widely used. Classification of the peat underneath is much more

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[5] Ibid., page 5

time consuming and more difficult, and therefore less frequently applied. The third facet, topographical designation, has met with lesser acceptance. Neither of the latter two designations were applied to the muskeg areas utilized in this project.

A fourth facet of muskeg classification has been proposed, based on airform patterns revealed in aerial photographs taken at 30,000 foot altitude. In this regard, five patterns which are observable and identifiable from the aerial photographs have been designated as: dermatoid, stipploid, terrazzoid, marbloid, and reticuloid.[6] These terms are derived from the characteristic nature of the patterns evidenced on the aerial photographs. The correlation of these airform patterns with physical properties remains to be established, although some work has been done in correlating muskeg classification according to Radforth's coverage designation with the five airform patterns.

MUSKEG AREAS UTILIZED IN THE PROJECT

The muskeg areas utilized in this project are all located in the Upper Peninsula of Michigan, with the principal ones being located in Keweenaw, Baraga, Alger and Luce Counties, Fig. 1.

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[6]Radforth, N. W., Muskeg Access with Special Reference to Problems of the Petroleum Industry, Canadian Mining and Metallurgical Bulletin, LIX: 531: 271-277, 1956.

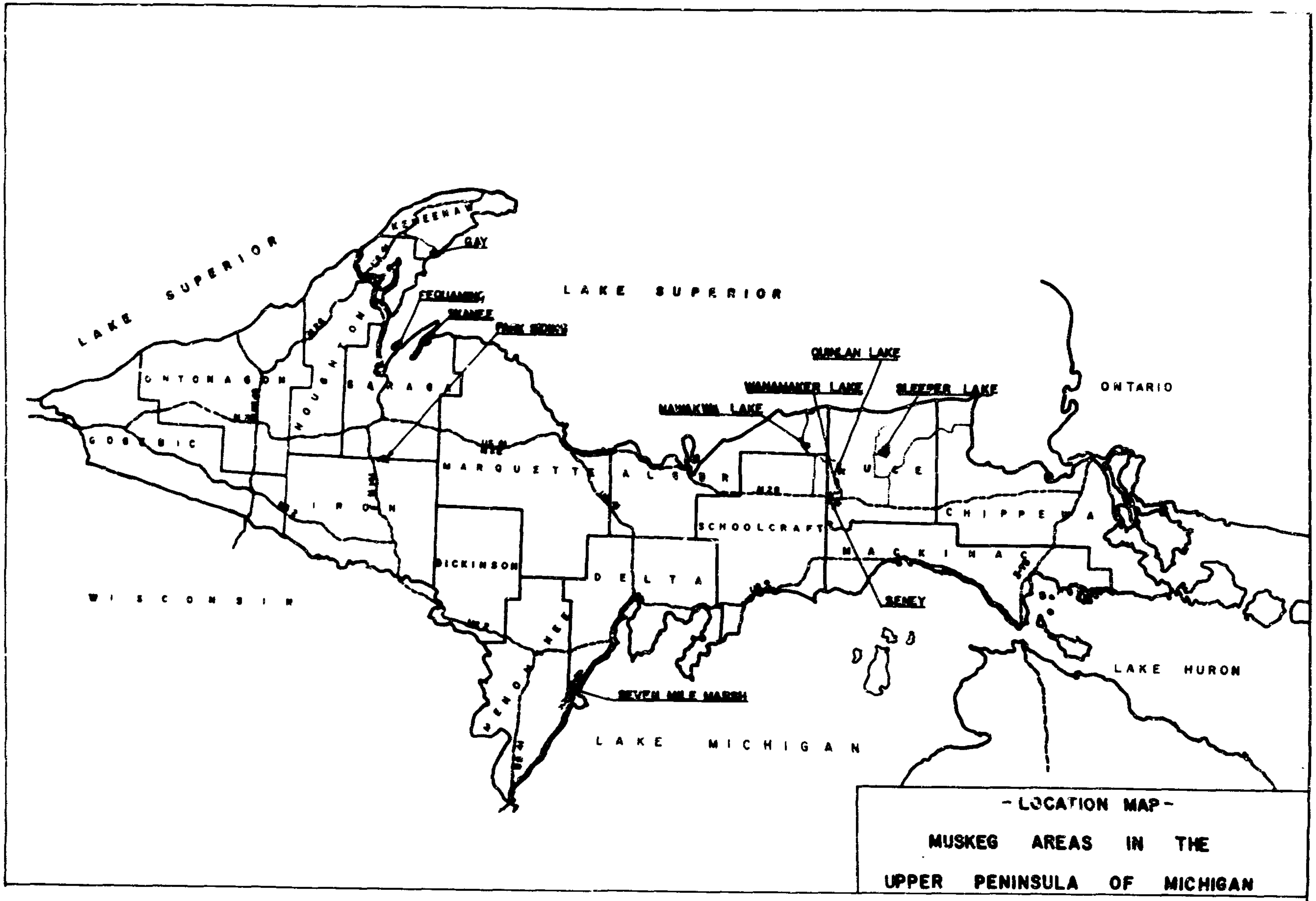


Fig. 1 - Muskeg Areas in the Upper Peninsula of Michigan

Most of these areas would be classed as confined muskeg, with possibly the exception of the Sleeper Lake Area muskeg in Luce County. This is several miles in length and shows the characteristic uniformity in depth and in the mat and peat characteristics typical of unconfined muskeg.

The most widely used areas were the Gay Area (Keweenaw County), the Pequaming and Skanee Areas (Baraga County), and the Sleeper Lake Area (Luce County). These areas classify primarily as Radforth F, FI, FIE, or IF. A complete list of all areas investigated is included in the Appendix.

EXPERIMENTAL PROGRAM

The experimental program consisted of four somewhat concurrent phases. One phase was the development and construction of test equipment that would make possible the evaluation of muskeg characteristics. A second phase consisted of making a large number of various tests in muskeg areas of the Upper Peninsula of Michigan. The survey and classification of these muskeg areas comprised a third phase of the program. In the fourth phase the test data was analyzed, and an attempt was made to use it in predicting vehicle performance on muskeg.

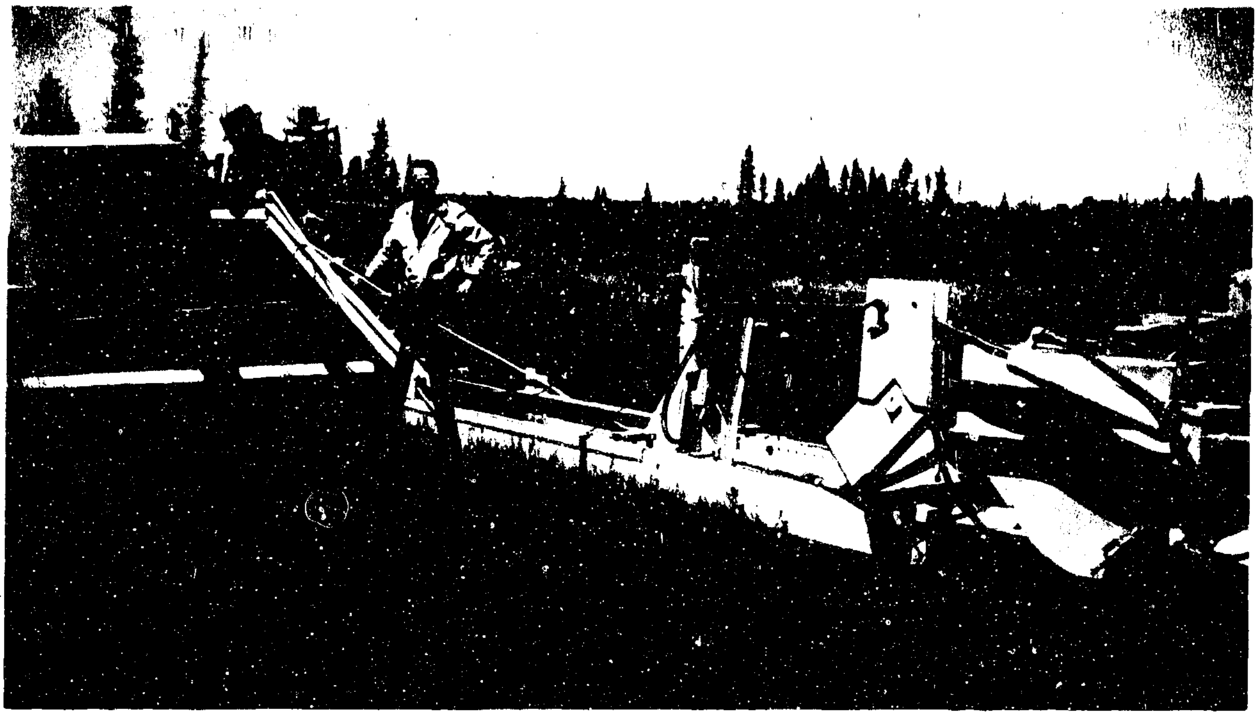
EQUIPMENT DEVELOPED

Muskeg Bevameter

Because of surface variations frequently found on muskeg terrain a Bevameter apparatus had to be designed to handle larger plates than those normally used on similar type equipment. Consequently the loading capacity of the machine had to be much greater than in those normally used on conventional mineral soils.

The machine that finally evolved was mounted on the rear of an M29C Weasel, Fig. 2 & 3, and consisted of a trunnion-mounted frame which could be hydraulically actuated from its transport position to the testing position. The free end of the "boom" was designed to connect through an adjustable linkage to a second M29C Weasel. In this manner, the combined weight of two M29C Weasels could be utilized as reactions on the ends of the test frame, or at least a substantial portion of this weight was thus available.

The M29C Weasel which was used for transporting the Bevameter-type test frame was equipped with the necessary hydraulic equipment and controls to actuate the test frame into operating position, and to supply the hydraulic power for the plate loading cylinder. The second M29C Weasel in the test rig



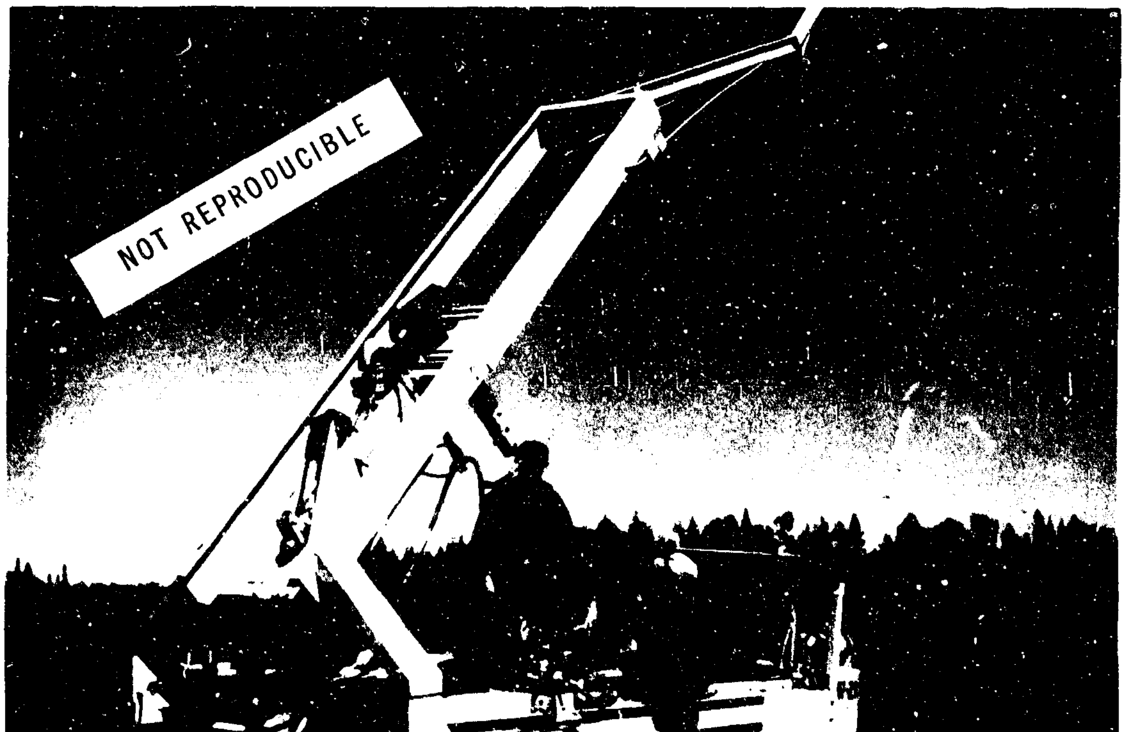


Fig. 2 - Muskeg Rig

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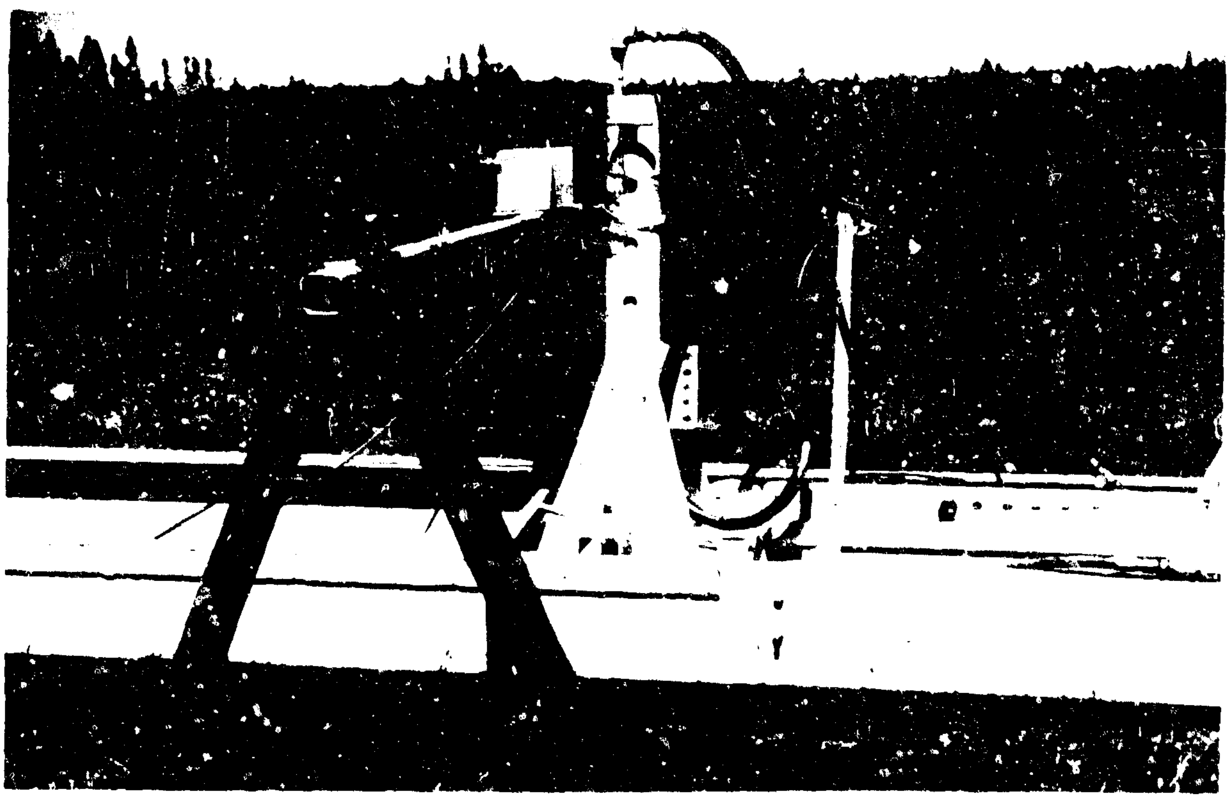

Fig. 3 - Muskeg Rig

provided the electrical power and carried the necessary recording equipment. The amphibious capabilities of the M29C Weasels proved to be essential on a number of occasions during the testing program, even though the rig-transporting Weasel was loaded beyond its limit for truly amphibious operation.

The sinkage-test loading cylinder was also used to provide a normal load for the shear test, through an adjustable pressure regulator; and the carriage on which it was mounted was capable of being moved horizontally on tracks within the test frame by a second hydraulic cylinder.

Both the vertical force in the sinkage test and the horizontal force in the shear test were measured by tension-compression type strain-gage load cells, and the displacements were measured by potentiometric type displacement transducers. The electrical signals from these devices were communicated to an X-Y Recorder to provide a direct plot of load versus displacement in both the sinkage and shear tests. The reference point for the displacement transducers as provided by an A-frame supported on the muskeg surface, sufficiently far enough away so as not to be affected by the displacement of the loaded area.

For many of the plate sinkage tests, a second displacement transducer was used to measure simultaneously the displacement of the bottom surface of the muskeg mat. This showed the amount of compression in the mat as it was loaded.

The frame of the test rig was long enough to allow the movable carriage, which supported the loading cylinder, to be set in two different test positions for any given vehicle position. This was particularly beneficial in view of the time required to maneuver the M29C Weasels on the muskeg from one test set-up to the next.

As explained earlier, the "mat" on muskeg is the upper layer of the two strata normally found in muskeg. The plane of demarcation between the "mat" and the peat underneath was taken at the point where the interwoven fibers of the living cover and the partially decomposed dead fibers, immediately underneath, met the liquid-like peat. This demarcation plane was detected with a mat thickness measuring gage developed for this project, Fig. 4. In firm muskeg, where the moisture content in the peat was lower, this plane of demarcation was not as readily determinable.

It should be pointed out that the definition of "mat," as used here, is not necessarily in agreement with the definition used by other investigators, some of whom apply the term "mat"

Fig. 4 - Mat Thickness Measuring Gage

only to the living surface cover. Nevertheless, it was felt by the investigators in this project that vehicle mobility, or muskeg trafficability, is closely related to the character of the entire interwoven and fibrous layer that "floats" as a load-supporting membrane on the liquid-like peat underneath.

Shear Test Apparatus

The shear-test data obtained with the Muskeg Bevameter were of questionable accuracy due to friction in the carriage and the difficulty encountered in maintaining a constant normal load. A new shear apparatus was devised, as shown in Fig. 5. The device consists of an aluminum box having a bottom "shear" area of 288 square inches (12 inches wide by 24 inches long). Lead weights (28.8 pounds each) are used to obtain normal loads from 0.2 psi to 3.4 psi. The horizontal force is provided through a rope by the capstan drive of an M29C Weasel and is measured by a strain-gage type load cell. Slip in inches is obtained by means of a potentiometric displacement transducer.

Peat Sampler

A sampling technique was developed which allowed for the removal and examination of a relatively undisturbed sample of the peat. The sampling device consisted of a 3-inch diameter

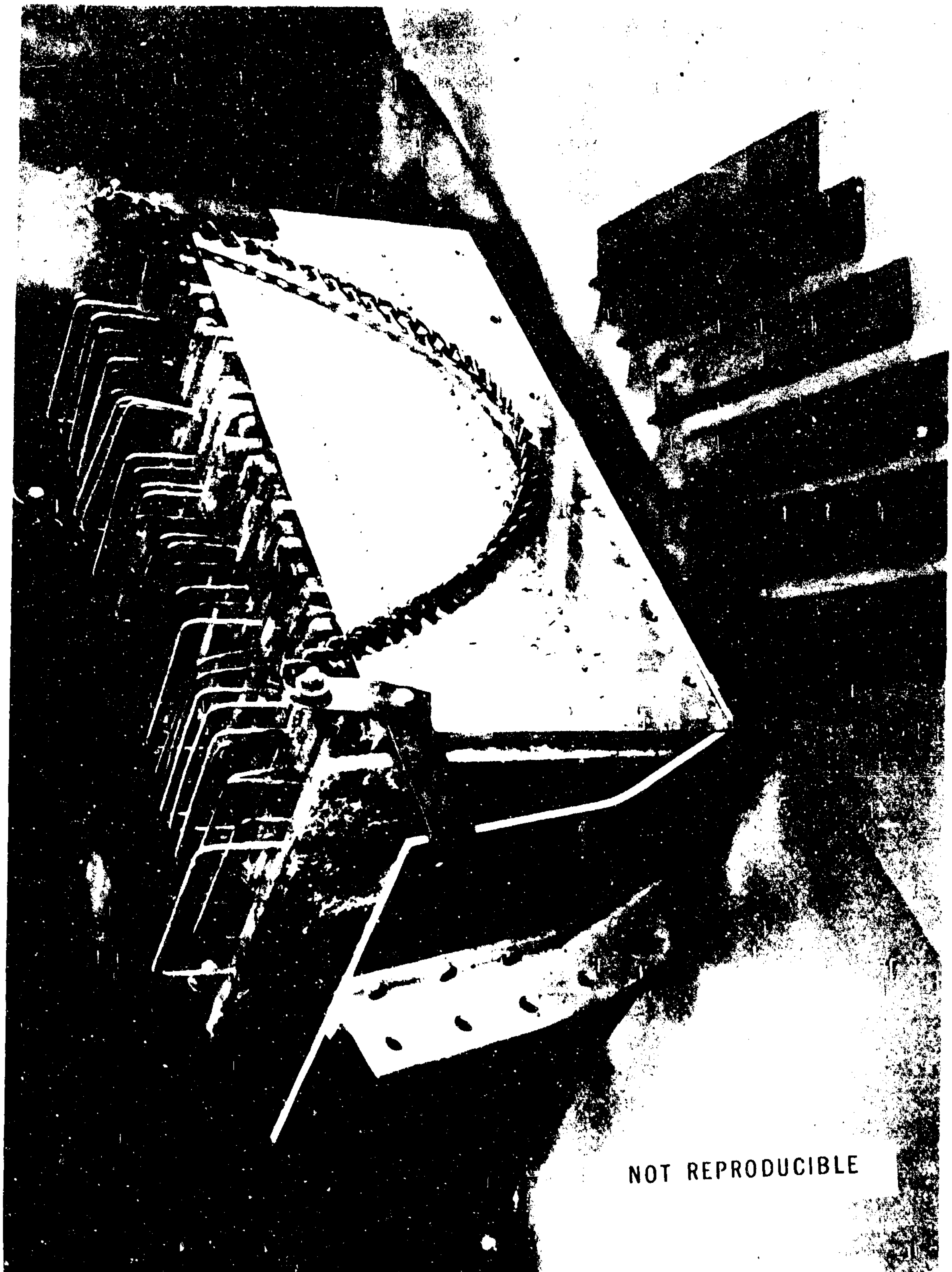

Fig. 5 - Shear Apparatus

aluminum tube which was introduced through a hole cut in the mat and pushed down into the peat. A larger plastic tube, equipped with an O-ring collar at its bottom, was pushed down over the 3-inch aluminum tube, creating an air space around it, Fig. 6. Pieces of "dry ice" were dropped into this air space, causing a plug of peat to freeze in the bottom of the aluminum sampling tube. In this manner, the peat sample in the tubes was removed from the muskeg, and low ambient temperatures in the winter caused the rest of the peat sample to freeze, making for easy handling, transport, and examination.

Tensiometer

A realization of the importance of the tensile strength of the fibers in the upper portion of the floating vegetative mat, led to the development of a device to measure this property. The "tensiometer," as the device is called, is shown in Fig. 7 and in field use in Figs. 8 and 9. Made almost entirely of aluminum (35 pounds), it is portable and easy to use, requiring only 2 to 3 minutes per test. The eight tines on each arm may be adjusted to test 3, 6, or 9-inch layers of surface mat. The load-displacement relationship is recorded directly on an X-Y recorder, through the use of strain gages on the arms and a displacement transducer.

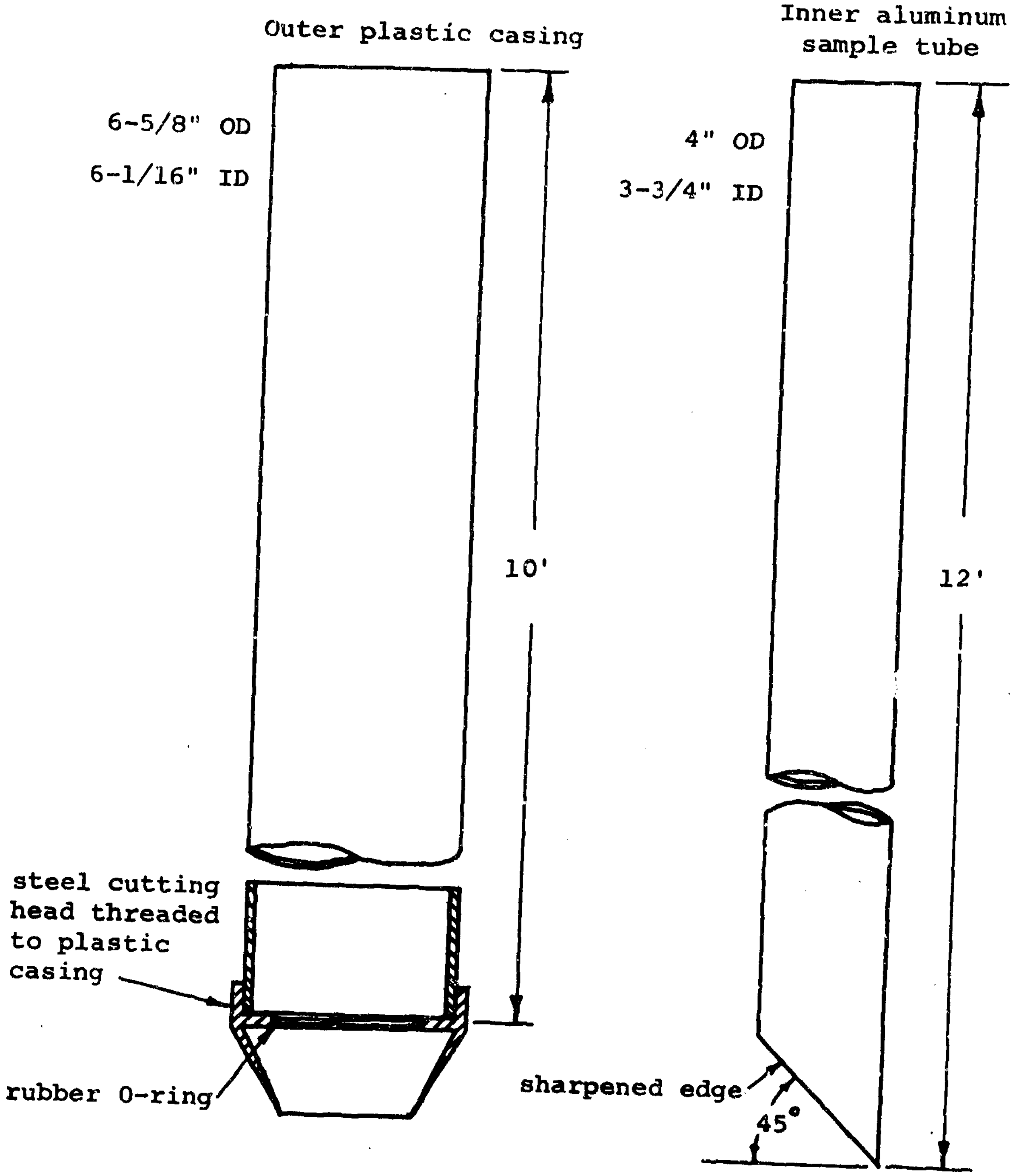

Fig. 6 - Peat Sampler

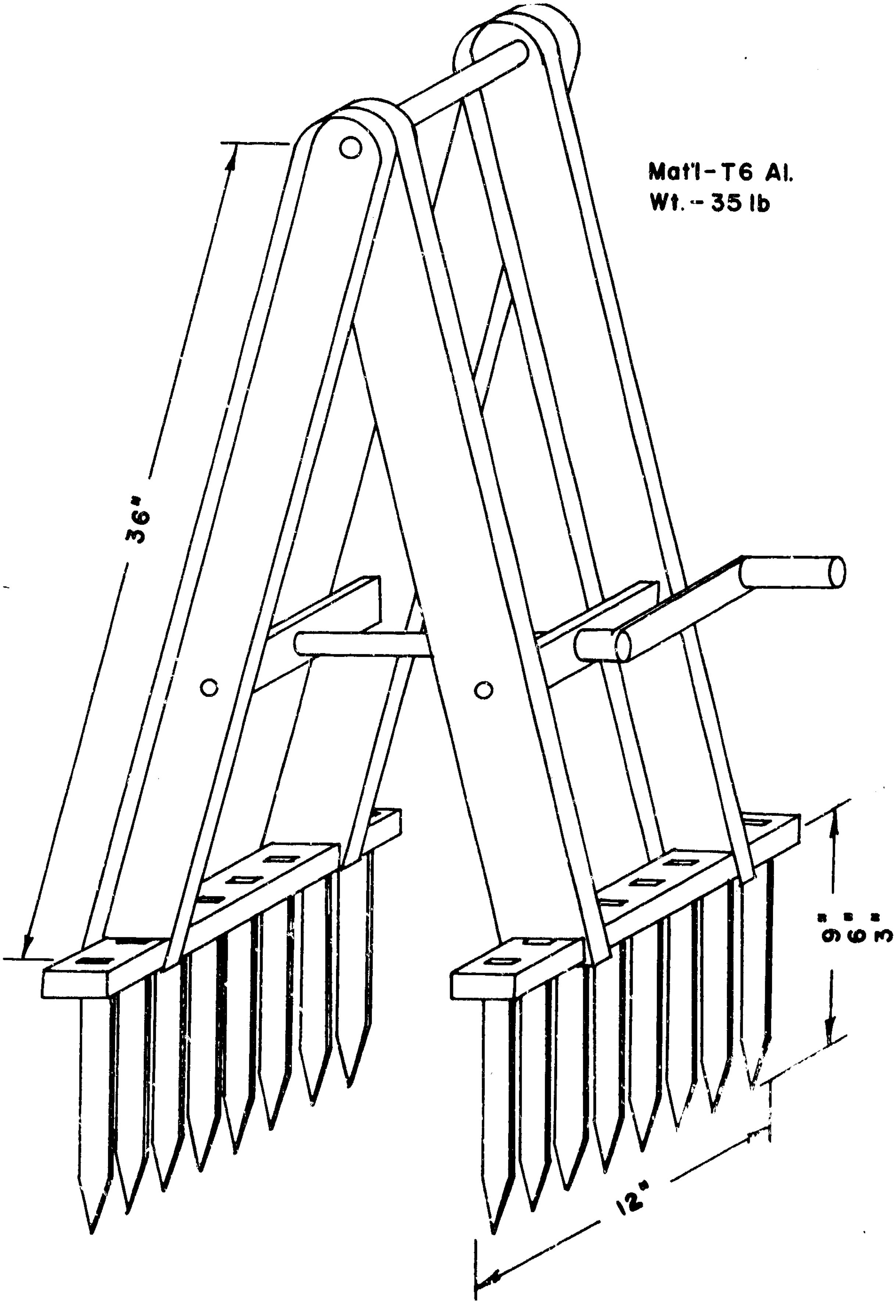

Fig. 7 - Tensiometer

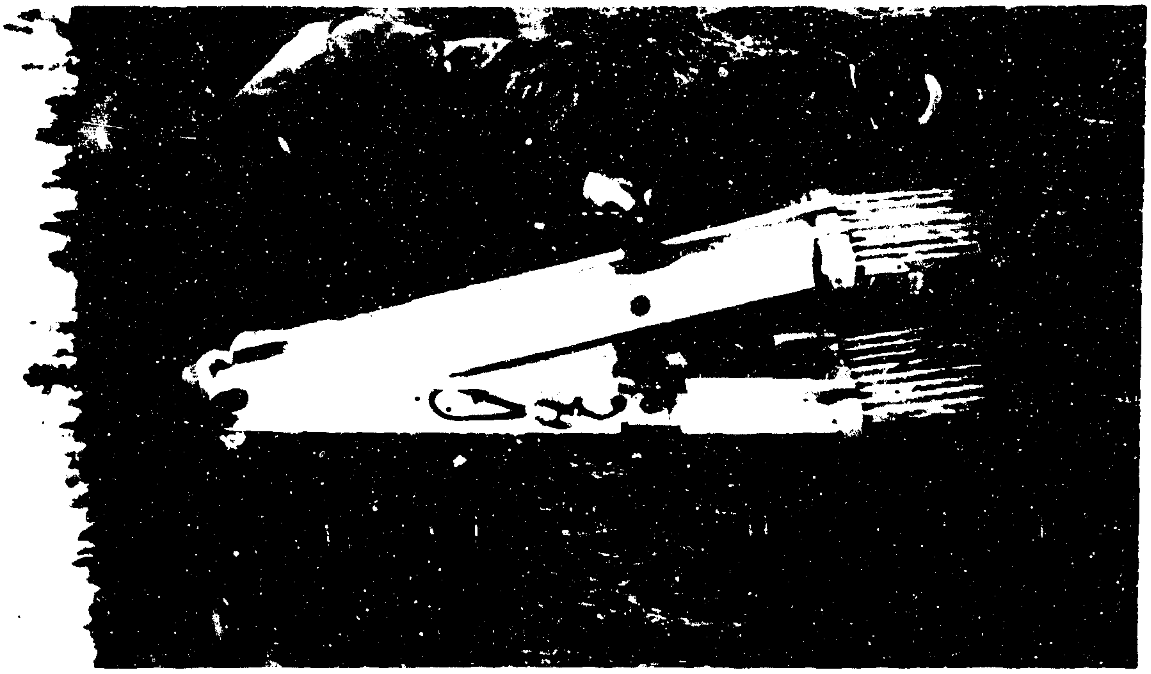

Fig. 9 - Tensiometer

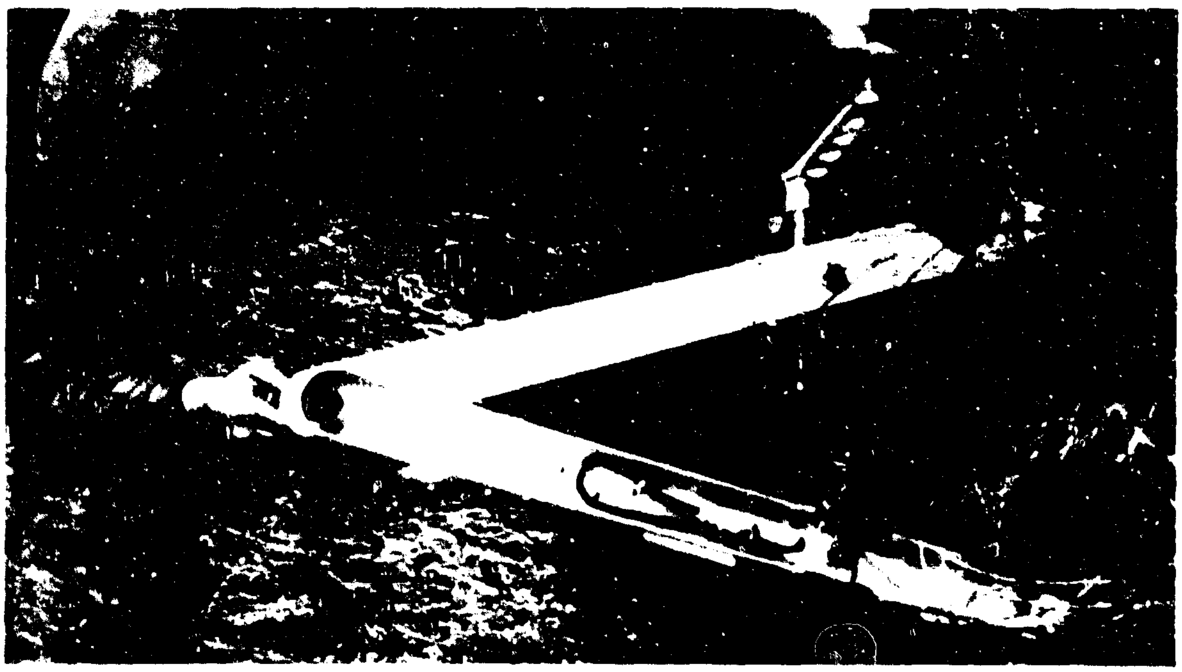

Fig. 8 - Tensiometer

TYPES OF TESTS

Load-Sinkage Tests

In the load-sinkage tests various sized plates were used, including 1 x 1 and 2 x 2 foot square, 1 x 2 and 1 x 3 foot rectangular, and 1, 2, and 3 square-foot circular plates. In addition, perimeter effects were investigated during a later phase of the project, by using a series of 5 to 1 aspect ratio rectangular plates whose areas were equivalent to circular plates ranging from 4 to 20 inches in diameter.

During the sinkage tests, simultaneous measurements were made of the displacement (sinkage) of the original surface layer and that of the bottom of the muskeg mat with potentiometric displacement transducers, registering directly on the recorders. This showed the amount the mat was compressed under loading as well as the amount of the surface sinkage.

Another variation of the conventional sinkage test was also performed during the testing program. In that muskeg trafficability failure usually occurs after some number of vehicle passes have been repeated on a giver surface, an attempt was made to simulate this during the sinkage tests. The load required to cause failure of the mat was first determined in a particular area. The loading device was then moved to an

immediately adjacent and similar area (using the movable carriage on the test rig), and the loading procedure was repeated, but at some load less than that which had previously caused failure. The load was applied repeatedly on the same spot until failure ultimately did occur, or until indications were that failure would not take place. The sinkage curves for each successive load application were plotted on the same set of coordinates, which thus showed the partial recovery of the loaded area as the load was relieved each time, as well as the residual displacement which occurred with each successive application.

Shear Tests

The first series of shear tests were made by using the movable carriage on the Test Rig, with 1 x 1 foot plate, equipped with two-inch saw-tooth grouzers, attached to the loading cylinder, which was used to maintain a given constant normal load. The horizontal pull was provided by a second hydraulic cylinder. Again the normal force and horizontal pulling-force were measured with strain-gage load cells and the displacement by potentiometric transducers, and both signals recorded directly on an X-Y recorder. This test method was later abandoned in favor of a revised test.

In the revised method, a sled-like box, equipped with various types of removable grousers on the bottom surface, was used as the shearing device. Lead-weights were added to the box, whose bottom was the test plate, to allow varying the unit pressure on the two square-foot test surface in increments of 0.1 psi, from a minimum value of 0.2 psi to a maximum of 3.4 psi. The horizontal force was measured by a strain-gage load cell and the displacement, or slip, by a potentiometric transducer.

Drawbar Tests

A latter phase of the muskeg test program consisted of actual drawbar pull tests conducted on several test sites. Soil values at these sites were determined to allow for analytically predicting drawbar pull versus slip relationships for comparison with experimental values. Both the M29C Weasel and the Thiokol Spryte vehicles were tested.

An M29C Weasel equipped with recorders was used as the load or dynamometer vehicle. Ground speed, test vehicle track speed, drawbar pull, and test vehicle attitude and sinkage were recorded as the vehicle was loaded from zero to stall load. All tests were conducted with the test vehicle operating in its lowest gear and its engine speed maintained approximately constant.

In addition, towing tests were conducted at speeds from 1 to 7 mph to determine the effect of speed on towing resistance on muskeg. This was compared to towing resistance on a level gravel road.

Tensiometer Tests

Tensiometer tests, described earlier, were made in a number of areas, and in conjunction with plate sinkage, shear, drawbar, and cone penetrometer tests. The results and comparison of these tests are discussed in a later section. Tensiometer tests were made with various length tines for comparison of the strength of the mat at depths of 3, 6, and 9 inches.

As an aid to understanding what the tensiometer really measures, a series of tests were made after using a chain saw to cut the mat between the two rows of tines, and also with cuts parallel to the direction of force application.

Cone Penetrometer Tests

Cone penetrometer tests were made during the drawbar tests, using both the 1/2 and 1 square-inch area cones developed by WES (Waterways Experiment Station). A change in the WES method was made by utilizing a sensitive strain gage load cell in place of the proving ring— dial indicator for force measurement, and a

potentiometric displacement transducer in place of visual observation of sinkage. A plot of load versus sinkage was thus obtained on an X-Y recorder. Tests could be made at the rate of about one per minute permitting a large number of trials to be averaged.

Sampling Methods

The muskeg mat in all test areas was measured and examined. A special mat thickness probe was used to determine the thickness of the physical load carrying mat. This thickness was recorded for each test taken. A chain saw was employed to cut a 12-inch by 12-inch plug out of the mat. This plug was pulled out and examined to note the composition and degree of decay of the floating mat.

In several of the areas, the peat sampler was used to obtain relatively undisturbed frozen cores of peat, which were stored in a cold room and examined in detail later. Longitudinal and transverse section of the frozen cores revealed the structure of the peat. Transverse sections one-inch high and three-inches in diameter were cut out of the frozen core at one foot intervals, and moisture content in each was determined.

DISCUSSION OF RESULTS

One of the original objectives of this investigation was to develop an analytical method for predicting vehicle mobility in muskeg, using muskeg soil values. It soon became apparent that conventional methods of obtaining soil values were not readily applicable to evaluating muskeg characteristics. Consequently a great portion of the investigative effort was concentrated on developing new techniques and apparatus for measuring the properties of muskeg which relate to vehicle mobility.

LOAD-SINKAGE RELATIONSHIP

The load-sinkage relationship of a soil has a bearing on vehicle mobility. This characteristic of muskeg was investigated by means of a scaled-up version of a Bevameter, capable of using plates up to 3 square feet in area, applied with a force of 5,000 pounds, and consequent sinkage up to 36 inches.

Plate Sinkage Tests

A great many plate tests were made on all of the muskeg areas investigated in the Upper Peninsula of Michigan, on floating mats as thin as 10 inches, to mats over 6 feet thick.

A typical X-Y recorder plot obtained with this type of test is shown in Fig. 10. This same data can also be plotted on log-coordinates, Fig. 11, which then permits the determination of the moduli of sinkage, k_ϕ and k_c, as well as the sinkage exponent, "n," from the equation

$$p = \left(\frac{k_c}{b} + k_\phi\right) z^n$$

The data of Fig. 11 shows considerable difference in the sinkage exponent, "n," for three separate areas, although the mat had the same composition and depth in each case. The load-sinkage relationship for each of these areas was different because of varying strengths of the peat. This led to the investigation of the load-sinkage relationships of peat discussed later in the report.

Mat Compression

In general, sinkage results from the deflection of the floating mat down into the peat and a compression of the mat fibers under the plate. The test set-up shown in Fig. 12 was used to obtain data as shown in Fig. 13, where a 21-inch thick mat was compressed to 7 inches during a plate sinkage of 23 inches. Figure 14 shows a 37-inch mat being compressed a lesser percentage and failing at 22 inches of plate sinkage.

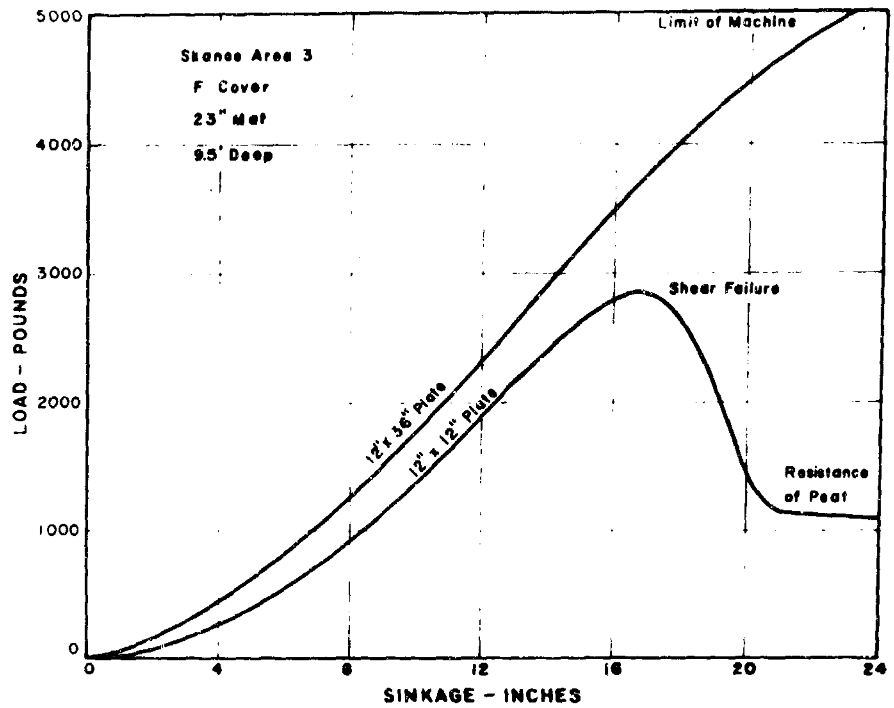

Fig. 10 - Plate Sinkage Tests

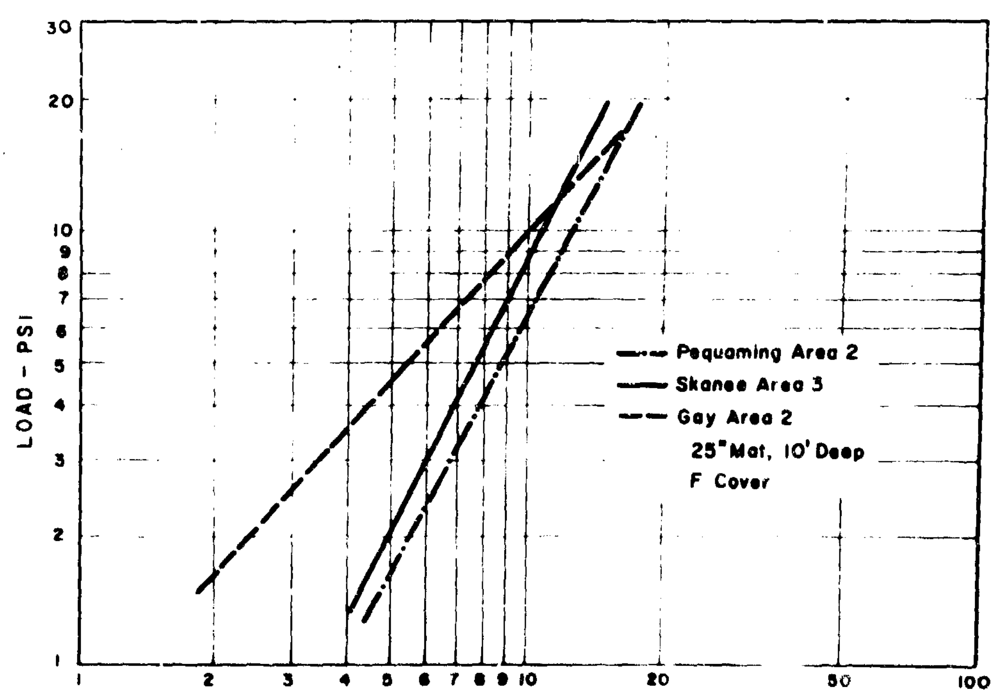

Fig. 11 - Plate Sinkage Tests

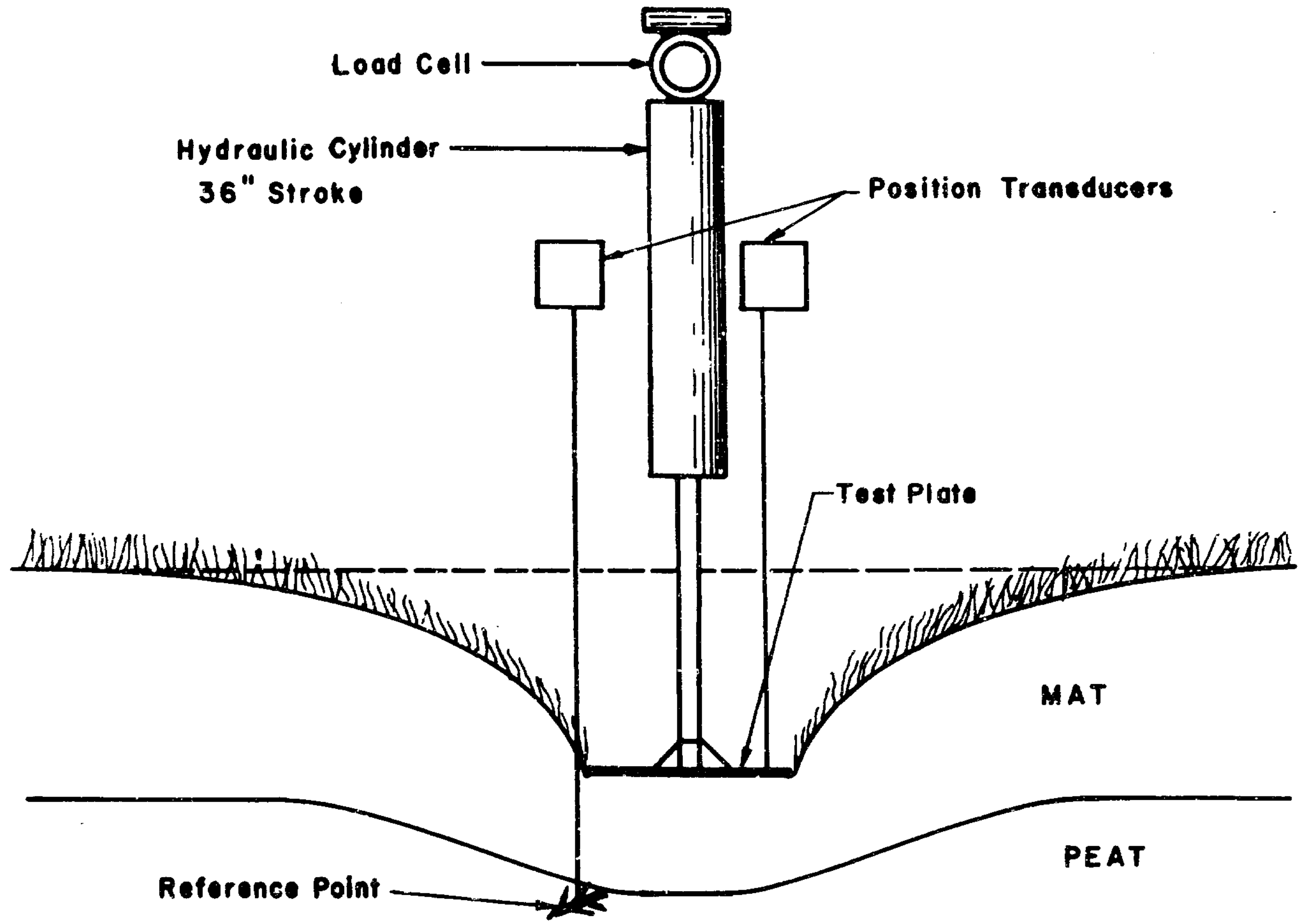

Fig. 12 - Mat Compression Test Set-up

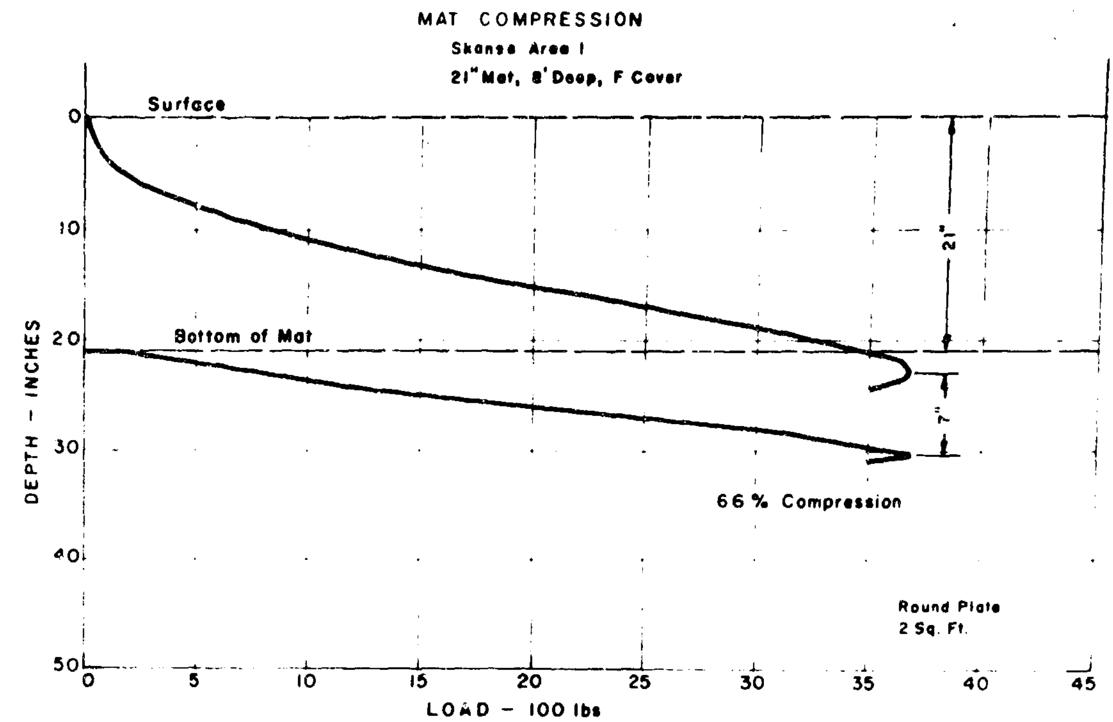

Fig. 13 - Mat Compression Data

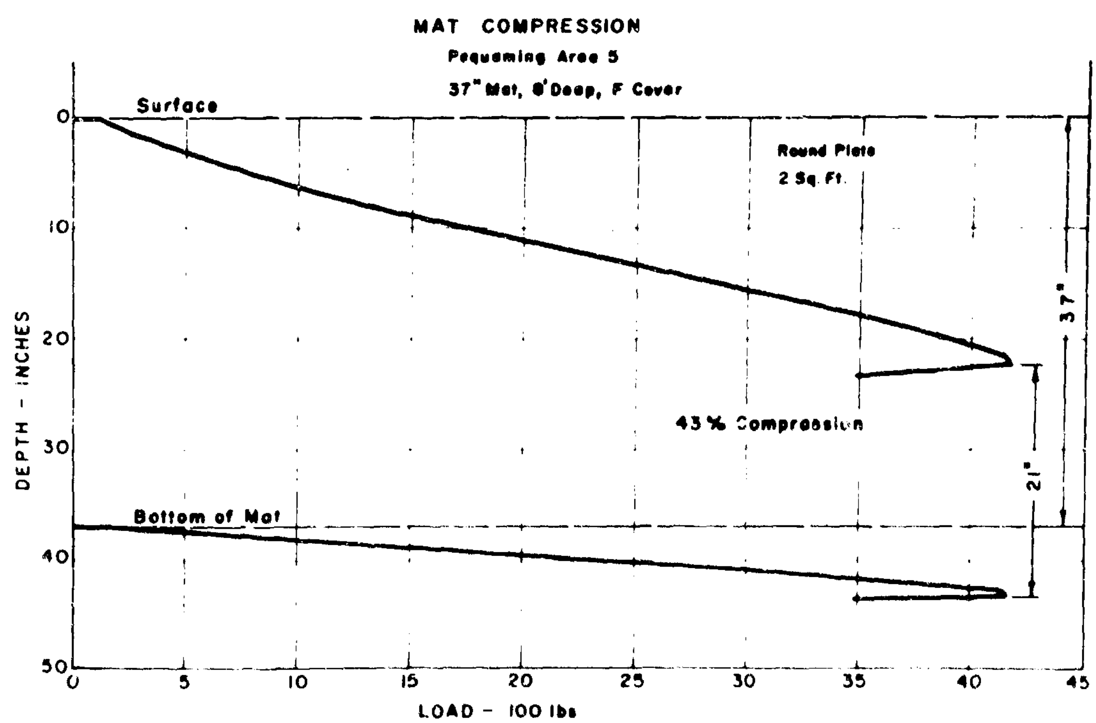

Fig. 14 - Mat Compression Data

In most of the tests, the sinkage at the bottom of the mat did not begin until several seconds after the beginning of the test, or until a considerable sinkage of the surface loading plate had occurred. Thus the initial portion of the load was taken up by compression of the mat, with little or none of it being transferred to the peat.

Plate Sinkage at Failure

A review of 56 plate-sinkage tests carried to mat failure showed an average sinkage of 22 inches at the point of mat failure. The standard deviation from the 22-inch mean was 2.2 inches indicating that 68 per cent of mat failures occurred within 19.8 to 24.2 inches of plate penetration.

The 56 plate-tests were all carried out with a 19.1-inch diameter round plate (2 square-foot area) in Radforth F or FI cover in the Skanee, Gay, Pequaming, Nawakwa, Quinlan, and Seney Areas. The mat thickness varied from 13 to over 72 inches, and the total depth from 4 to 30 feet.

The sinkage at failure appears to be independent of mat thickness and total depth. Ultimate failure results from a tensile failure of the mat fibers at the perimeter of the plate, as the mat is deformed by a plate sinkage of about 22 inches.

This would lead to the conclusion that the failure load is a function of plate perimeter rather than plate area, or at least a combination of the two, with perimeter playing the dominant role. It could also be concluded that the major portion of the plate load is carried by the living, fibrous material near the surface of the mat.

Perimeter Effect

The major portion of the load resistance in muskeg is caused by the top 6 to 12 inches of living vegetative mat. When the tensile strength of the fibers in this layer is exceeded, the mat fails. This tensile failure may be due either to the shear load imposed by the track grouzers, or the stretching of the mat because of vehicle weight. Figure 12 illustrates how a loaded plate results in the elongations of the upper-mat fibers.

The influence of the upper mat's tensile strength on load carrying ability can be demonstrated by plotting the plate load, in pounds per inch of plate perimeter, versus sinkage in inches as in Fig. 15. The six curves, each of which is the average of several tests, represent data for rectangular plates, all of 5 to 1 aspect ratios (length to width), and ranging in area from 12.6 to 314 square inches. The area to perimeter ratio (A/S) varied from 0.66 to 3.31 square inches per inch.

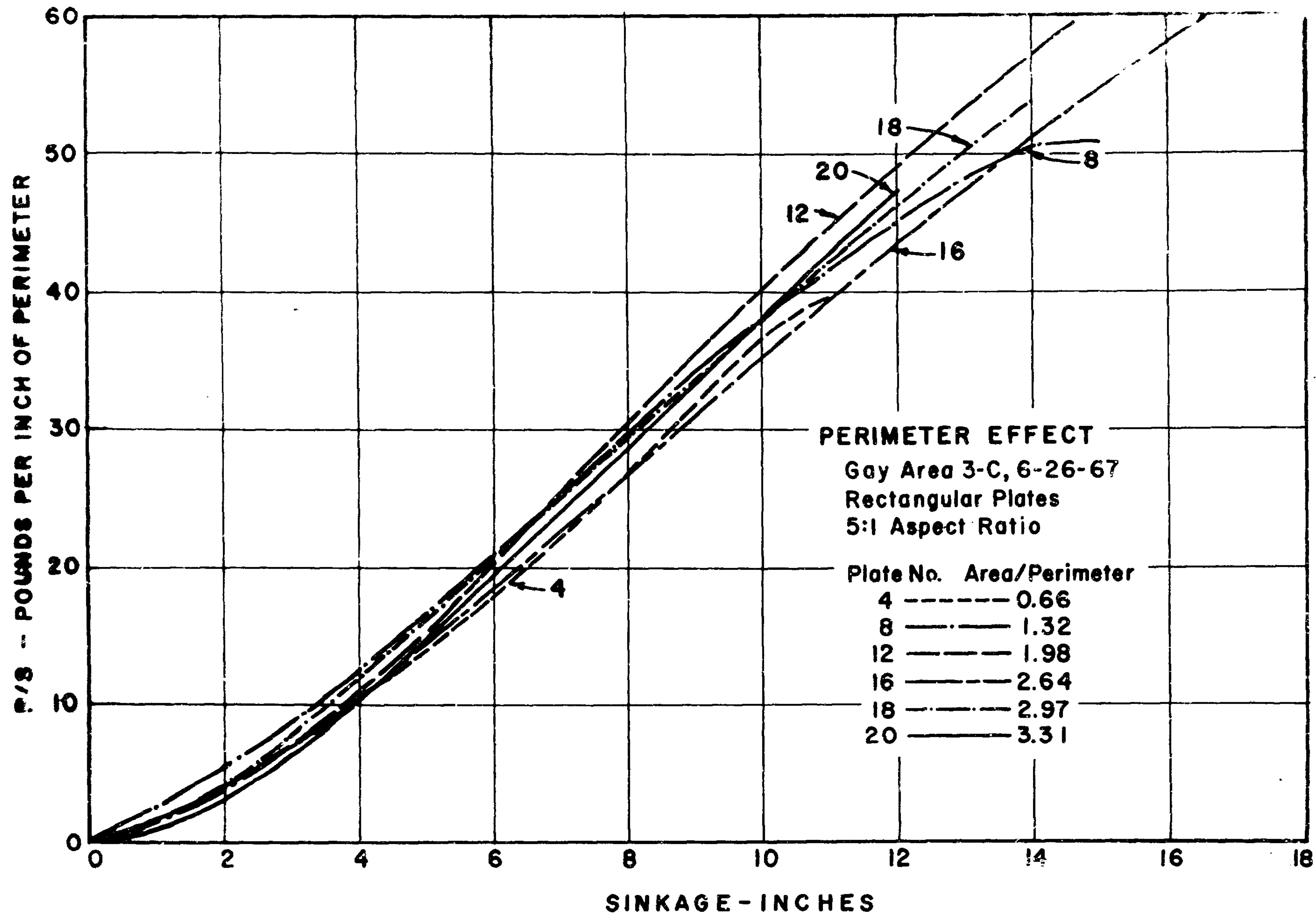

Fig. 15 - Perimeter Effect

The convergence of these six curves seems to indicate that the load carrying capacity of muskeg mat is principally a function of the tensile strength of the upper mat fibers.

Variable Area Mat Compression

The effect of plate size on the load-sinkage characteristics is shown by comparison of the results obtained with circular plates of one, two and three square-foot area, Fig. 16. When the load is plotted against the sinkage, the load at a given sinkage increases with the plate size, as would be expected. However, this increase is not linear with the plate area because of the perimeter effect. The movement of the bottom of the mat, however, is very nearly the same for all plates; that is, displacement varied directly with total load, independently of plate area.

When the same data are plotted as sinkage versus contact pressure in psi, as in Fig. 17, it can be seen that the contact pressure at a given sinkage decreases as the plate area increases. This is in general agreement with the behavior of the plate bearing tests on mineral soils. The displacement of the bottom of the mat follows the same pattern.

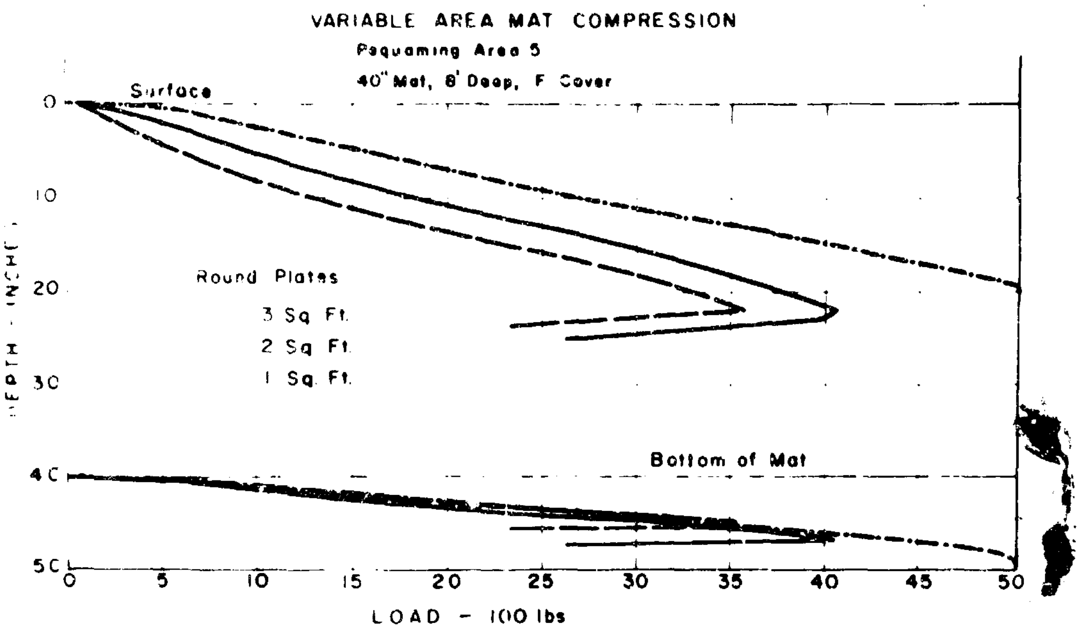

Fig. 16 - Variable Area Mat Compression

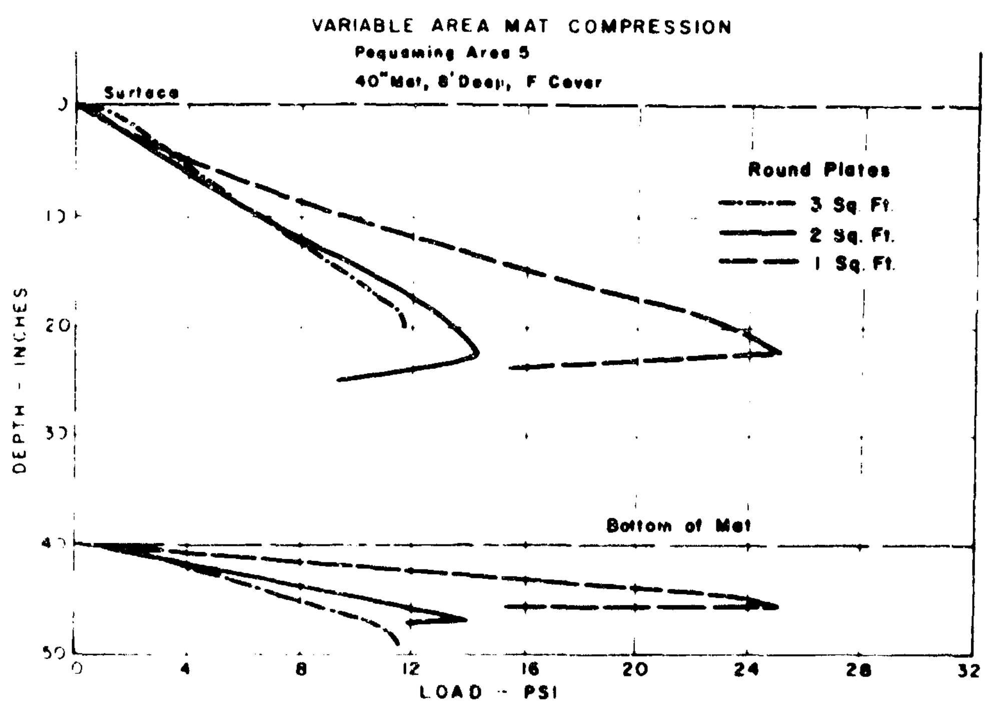

Fig. 17 - Variable Area Mat Compression

Some comparison may also be made regarding the amount of compression of the mat. For example, at a contact pressure of 10 psi, the original thickness of 40 inches is compressed to 31.5, 30, and 31 inches for plate areas of 1, 2, and 3 square feet, respectively. Thus, it appears that the compression depends on the contact pressure, but not on the plate area. When the conditions at failure are investigated, however, it appears that the amount of compression decreases as the plate size increases. For example, using the same data discussed above, the original thickness of 40 inches is compressed to 23, 25, and 29 inches for plate areas of 1, 2, and 3 square feet, respectively. Furthermore, the plate sinkage at failure is about 22 inches $\pm$ 2.2 inches for all three plates.

Repeated Load Tests

Experience shows that a given vehicle may successfully cross a given muskeg once, or perhaps several times. With repeated passes, however, the vehicle may break through the mat and become immobilized. A series of repeated load tests was made in an effort to develop quantitative information regarding this behavior. These tests were instrumented and carried out in much the same manner as the mat-compression test, except that the magnitude of the repeated loads had to be limited to values less than the failure load. Loads of 50, 60, 70 and 80 per cent of failure loads were used.

The first step in the procedure was to determine the failure load. This was done by making a mat compression test in the conventional manner. The peak load obtained from this test was then multiplied by the selected percentage factor to establish the load limit for the repeated-load test.

The plate and loading cylinder were then moved to the alternate position on the beam, so that the repeated test could be run on a virgin area, yet one that was relatively close to the point at which the failure load was previously determined. The load was allowed to build up only to the calculated limit, then removed. The loading and unloading cycles were thus repeated until the mat failed, or until a large number of repetitions had been made. As would be expected, the number of repetitions before failure was small when the repeated load was high, as for 80 per cent of the failure load in Fig. 18. For lighter loads the number of repetitions to failure increased, Fig. 19. At 50 per cent of the failure load, the test was normally halted at 50 repetitions as shown in Fig. 20, or continued to failure to determine the effect of the repetitions on the ultimate strength.

The recovery of the mats are also shown in these illustrations, which are actual X-Y recorder plots. In most cases, the mat returned to within 6 inches of their original levels, even after numerous loadings. No increase in recovery of the mats was noted by waiting, even up to an hour, between repeated loads.

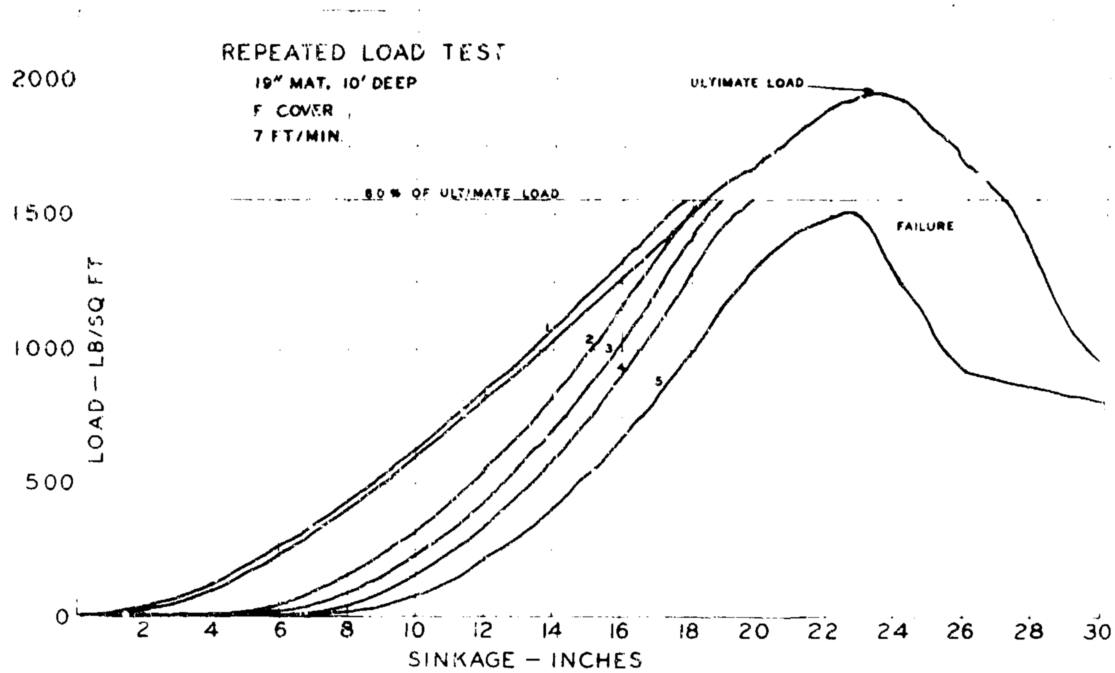

Fig. 18 - Repeated Load Tests, 80%

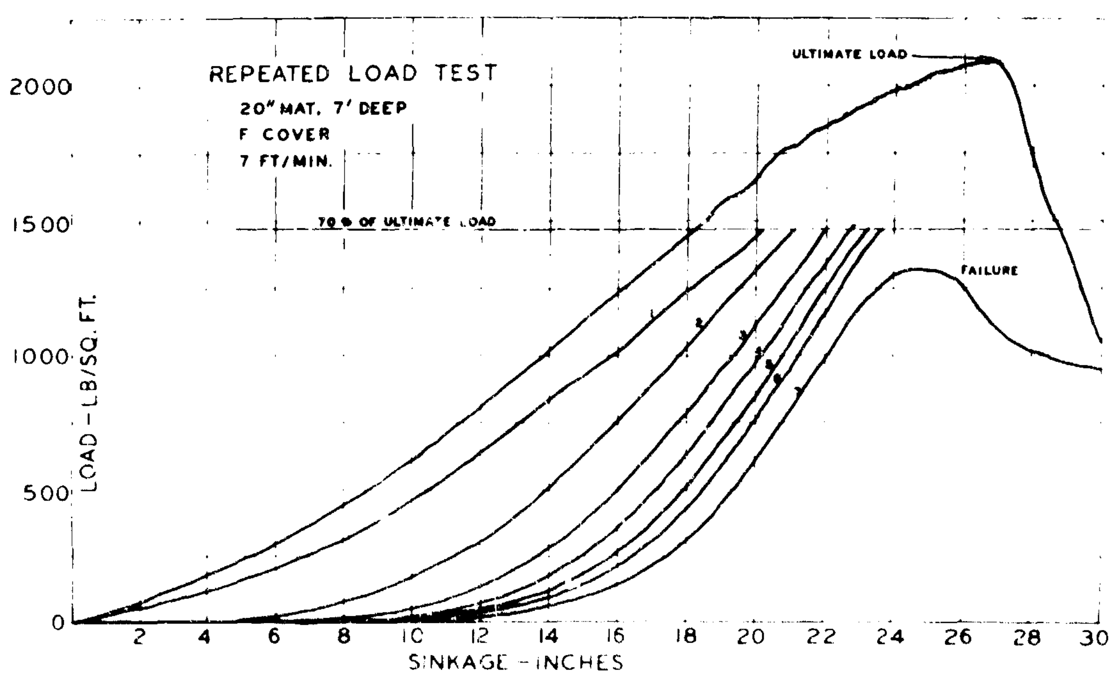

Fig. 19 - Repeated Load Tests, 70%

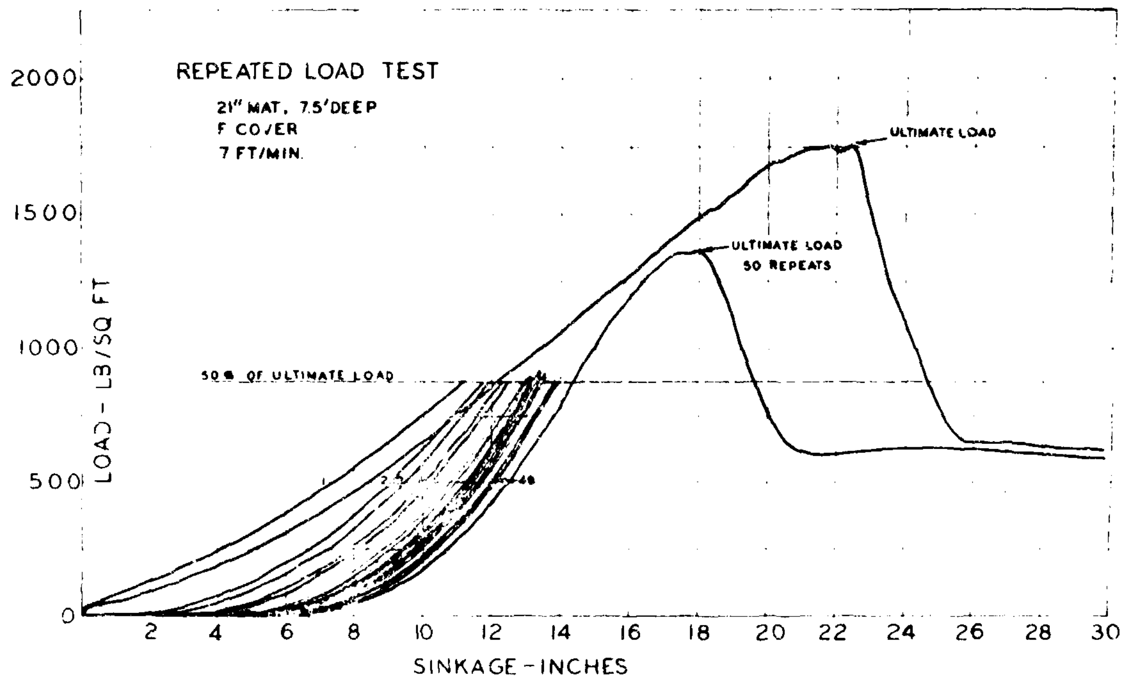

Fig. 20 - Repeated Load Tests, 50%

In general, several days are required for more complete recoveries to the original surface levels.

PEAT

The peat sampler previously described permitted an examination of the structure of peat at various depths. Figure 21 shows cross sections of frozen samples at four different depths. The structure, orientation, and size of fibers may be readily seen. The frozen peat samples were also sliced transversely at one-inch intervals, and water content determinations were made at the various depths.

The peat found in the several areas investigated, varied considerably in water content and strength. In some areas, (Sleeper Lake South) the peat was firm and well consolidated, with water content in the order of 200 to 300 per cent. In other areas (Gay, Skanee), the peat was extremely weak and very high in water content, (up to 1500 per cent) as shown in Fig. 22. Strength tests of the peat were carried out with a cone penetrometer in several areas, particularly in the locations where peat samples were taken. The cone used had a major diameter of 3 inches and a cone-angle of 15 degrees.

a. at 70-inch depth

b. at 84-inch depth

c. at 90-inch depth

Fig. 21 - Frozen Peat Samples

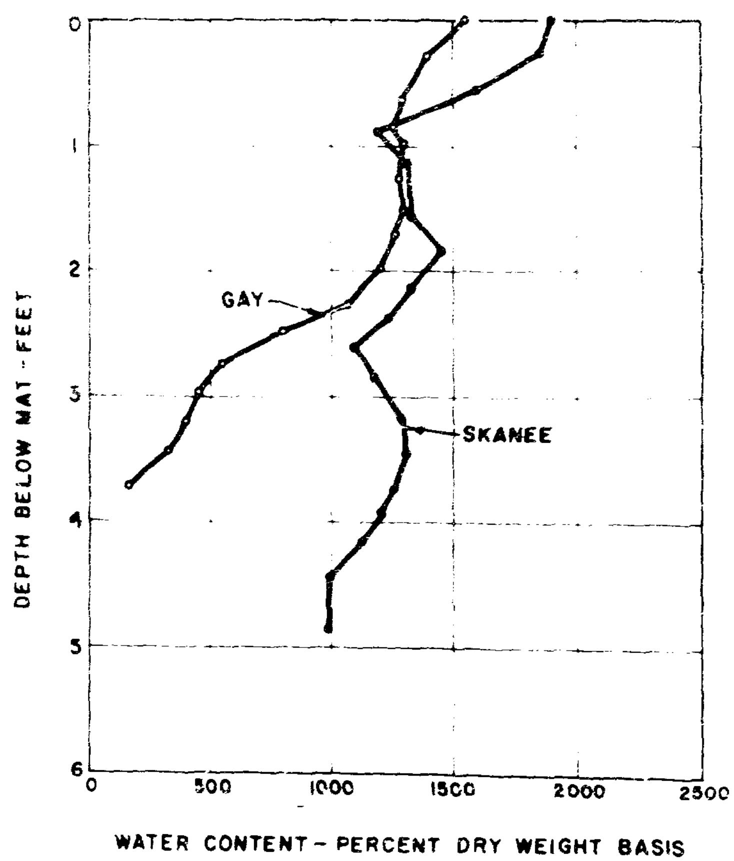

Fig. 22 - Moisture Content of Peat

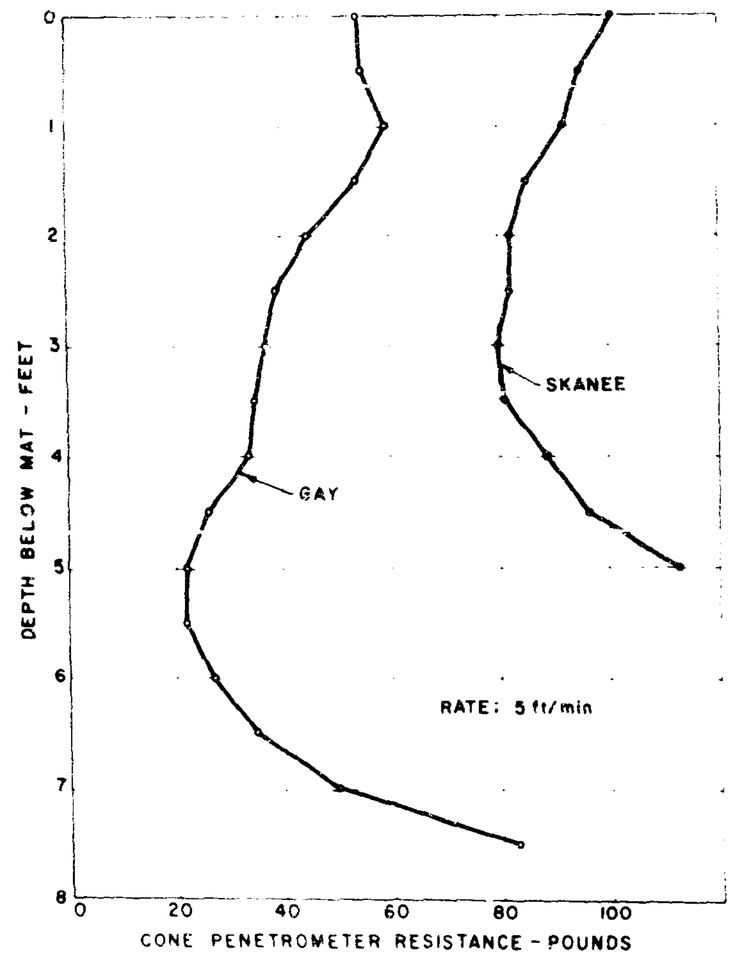

Fig. 23 - Peat Strength

Averages of the results of several tests in the Skanee and Gay areas are shown in Fig. 23. The resistance of the Skanee peat is twice that of the Gay peat, although the water contents are about the same for each. The difference may be attributed to the structure of the peat. At Skanee, the peat is made up largely of fine organic fibers, while the Gay peat is much coarser in structure.

The difference in the strength of the peats undoubtedly is partially responsible for the difference in the plate-sinkage test results for the two areas, as shown in the log-log plot in Fig. 11. The rate of load increase with sinkage is much less for the Gay muskeg than for that at Skanee. The Pequaming area is near Skanee and its muskeg is quite similar.

Plate sinkage tests were also made directly on the peat. The mat was first cut with a chain saw and a 12 x 12 inch section of mat was removed, thus exposing the peat. An 18-inch box-like extension added to the 12-inch square plate made possible penetrations to 30 inches into the peat itself. The peat is made up of fine, decomposed organic material and also partially decomposed organic fibers of various sizes, plus water. Because of the fibrous nature of the peat, it appears plausible that its shear strength could vary considerably with rate of shear. Plate tests were carried out at various loading rates

from 1.5 feet per minute to 10 feet per minute. Typical curves of load versus sinkage (measured from bottom of mat) are shown in Fig. 24. Interestingly, the resistance of the peat is about 40 per cent greater at the lower loading rate.

A number of similar tests showed the same trend, indicating that peat exhibits a thixotropic behavior. It has considerable resistance to flow until its rate of flow is high enough to cause the fibrous particles to align themselves in the direction of flow.

It would appear from the above relationship that a slow traverse of muskeg would be desirable in order to take advantage of the higher load resistance of the peat at low loading rates. However, the percentage of the total load of a vehicle carried by the peat is relatively small. Compare Fig. 13, Mat Compression, with Fig. 24, Peat Compression, at 20 inches of sinkage. The total load carried by the muskeg is 3250 pounds or 1625 pounds per square foot, and this results in a 7-inch deflection of the bottom of the mat. In Fig. 24 at 7 inches sinkage into the peat we note that only 190 to 290 pounds per square resistance is developed by the peat, depending upon the loading rate. This indicates that only about 15 per cent of the plate, or vehicle load, is carried by the peat. This value is low, however, for it does not take into account the membrane-like

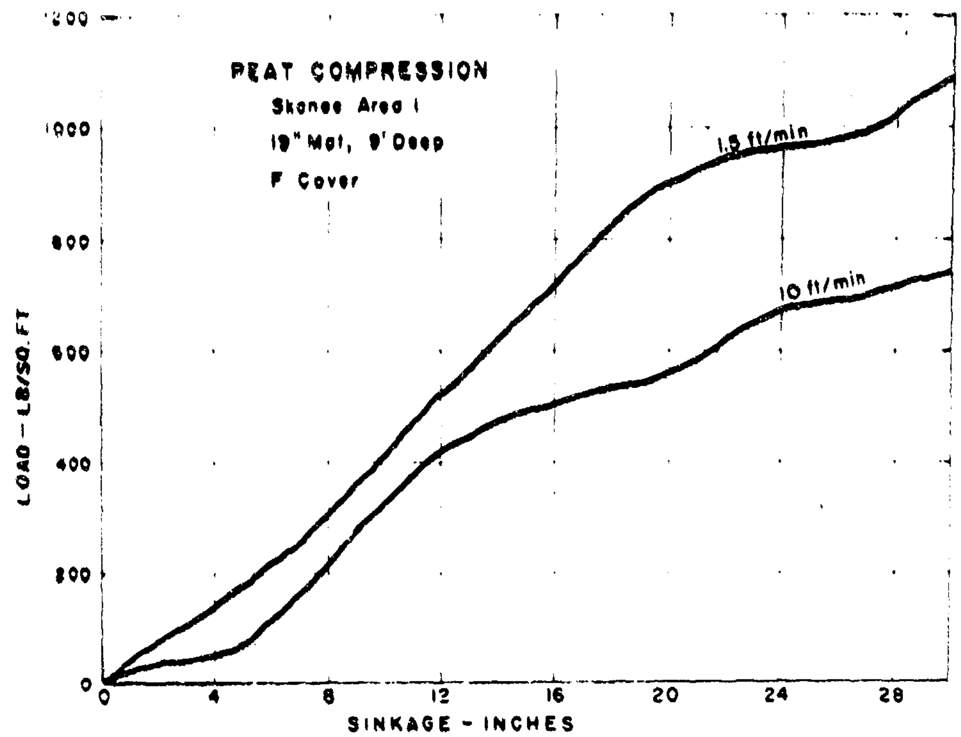

Fig. 24 - Variable Rate Peat Compression

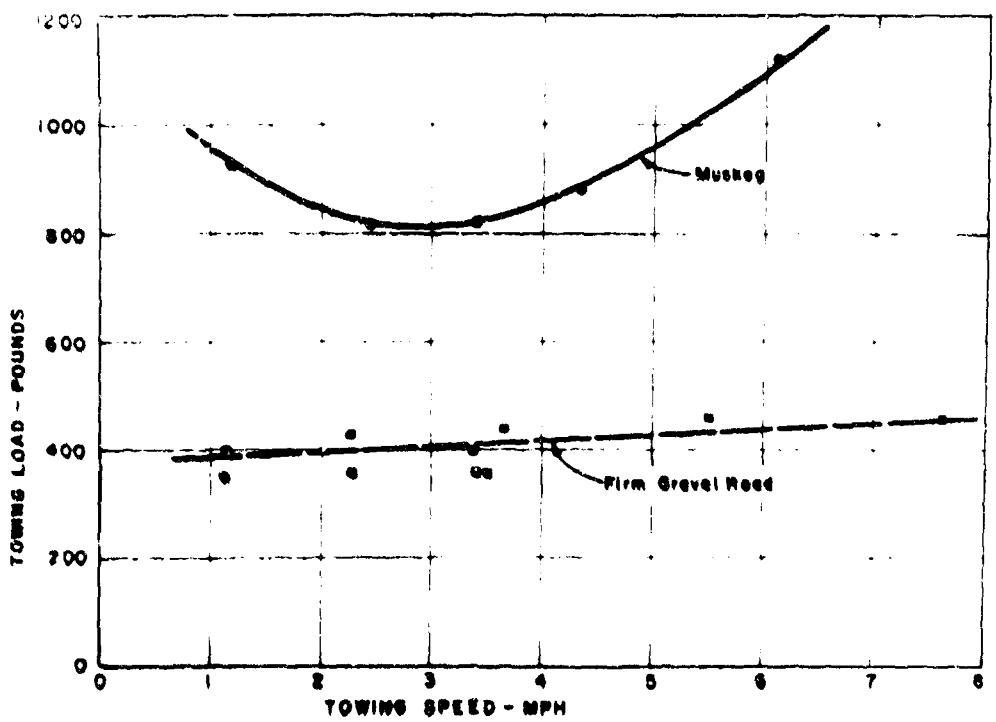

Fig. 25 - Towing Resistance of M29C Weasel

behavior of the muskeg mat. A one square-foot area plate or track section set down on the mat actually involves a much larger area of deflection at the bottom of the mat.

The benefits of greater load resistance of the peat, at low loading rates, is more than offset by the increased sinkage into the mat during a slow traverse of the muskeg by a vehicle. At lower vehicle speeds, a greater percentage of the tractive effort is expended in overcoming the compaction resistance, R_c, since vehicle sinkage into a given muskeg increases with time, up to a certain maximum. Vehicle operators have learned from experience that marginal strength muskeg is negotiated with greater certainty at higher vehicle speeds.

A quantitative indication of the effect of vehicle speed on compaction resistance was obtained in a series of towing tests carried out with the Thiokol Spryte and the M29C Weasel. Figure 25 shows the towing resistance of the M29C Weasel at various speeds on muskeg, compared to firm gravel. At very low speeds (1 mph), the sinkage of the towed vehicle was considerable, resulting in a tow-load equal to 10 per cent of the vehicle weight. As speed increased towing resistance decreased, until at 3 mph it reached a minimum. At all speeds, the towing load on muskeg was at least twice that encountered on a gravel road.

The behavior of a semi-fluid peat under a passing vehicle is illustrated in Fig. 26. The displacement of the peat is a function of the rate of loading, the amount of vehicle sinkage, and the mat compression. The effect of a vehicle pass on the strength of peat was investigated experimentally by a plate test. It was found that the strength of the peat, directly under the plate, was less after the plate sinkage tests, while the strength of the adjacent peat increased. A large 15-degree, 3-inch diameter cone penetrometer was used to measure the resistance, or strength, of the peat in each case.

The conclusion reached is that the solid material flows out from under the plate or track area and does not return immediately after the load is relieved. This has the effect of increasing the solid content of the adjacent peat and reducing it in the peat directly under the track. Therefore, successive passes of a vehicle might better be made by shifting over to the adjacent area, rather than repeating on the same track.

SHEAR TEST RESULTS

[illegible] of the muskeg properties investigated was "shear strength" of the mat. The term "shear" is used here, but although [illegible] in the same way as

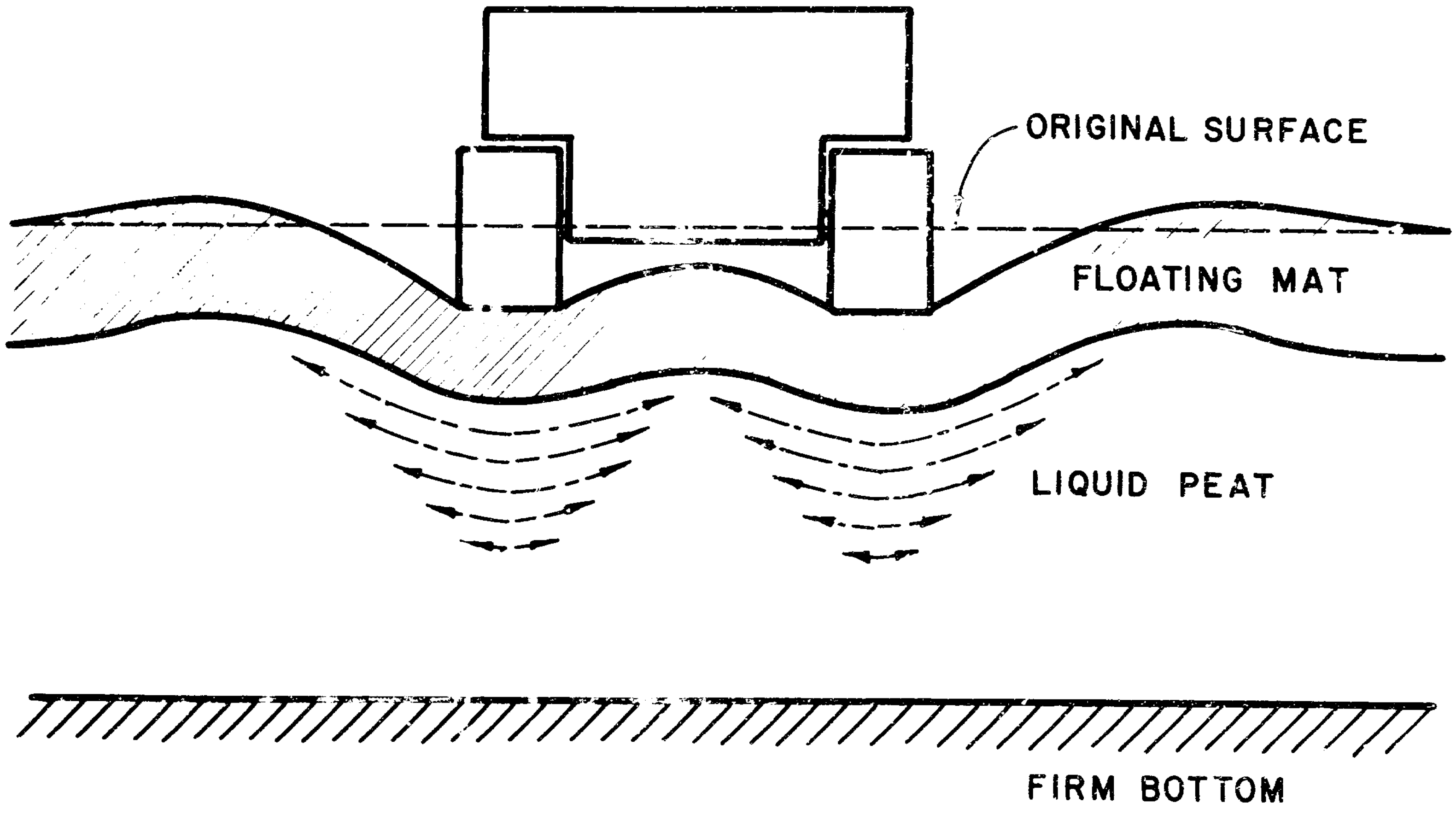

Fig. 26 - Vehicle Loading of Muskeg

for organic soils, their significance is not the same. Muskeg mat does not experience a "shear" failure, when subjected to a horizontal force in the presence of a normal force. Failure is actually a tensile failure of the fibers making up the mat. Whether the resistance of the mat to a horizontal force is called "shear strength" or given some other name, nevertheless its significance in regards to vehicle mobility is the same as that of shear strength of organic soils.

The apparatus shown in Fig. 5 was used to obtain "shear" data in several different muskeg areas. The device consists of an aluminum box having a bottom or "shear" area of 288 square inches (12 inches wide by 24 inches long). Lead weights (28.8 pounds each) are used to obtain normal loads from 0.2 psi to 3.4 psi. The horizontal force was provided through a rope by the capstan drive of an M29C Weasel and measured by a strain gage type load cell.

An X-Y recorder produced plots of "shear" stress versus slip directly as shown in Fig. 27. By taking readings at various normal loads a series of maximum shear-stress values can be plotted versus the corresponding normal-stress values as in Fig. 28. The slope of this plot, or the "shear stress" to normal stress ratio, can still be called tan $\emptyset$.

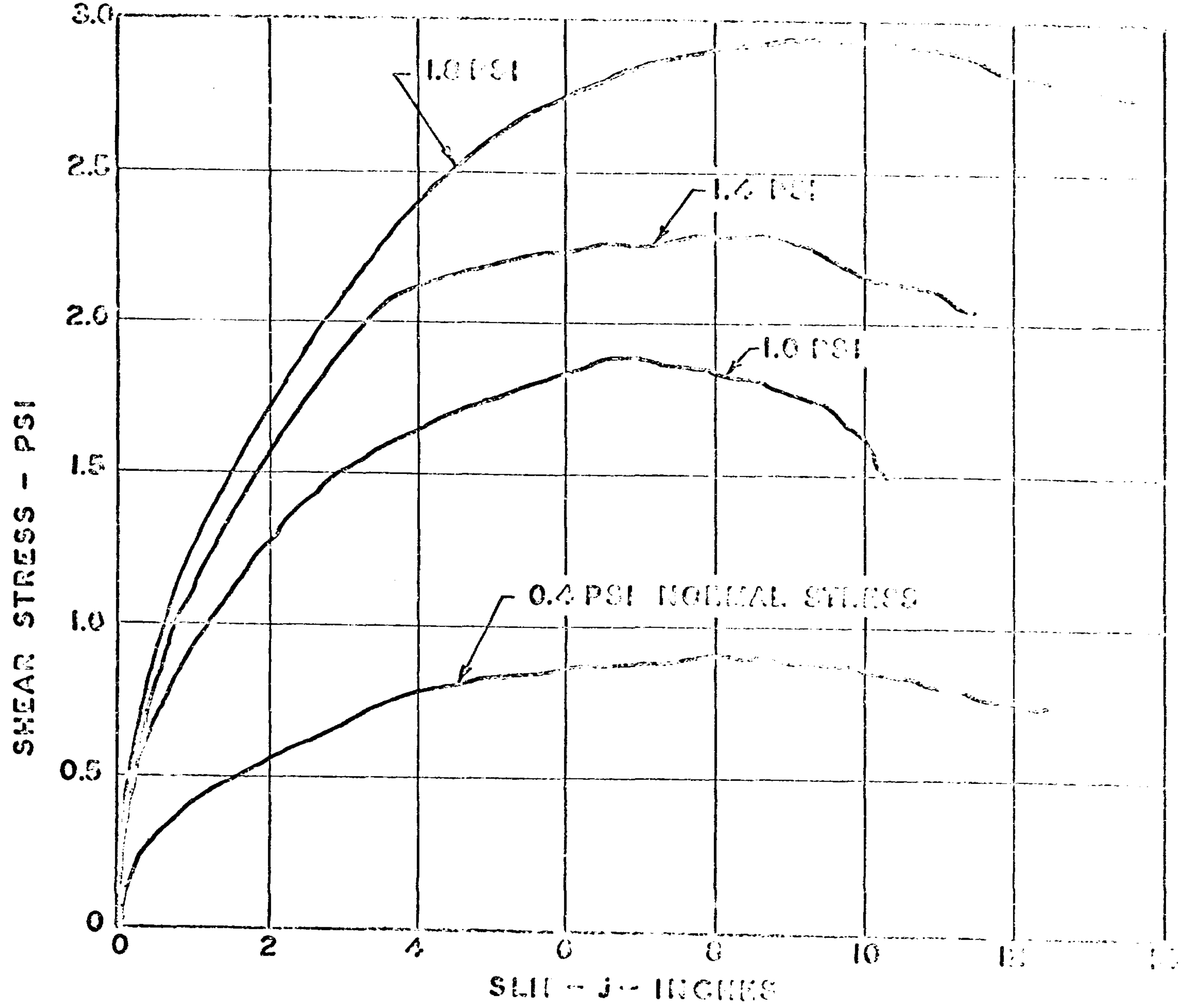

Fig. 27 - Shear Stress vs. Strain Curves for Muskeg

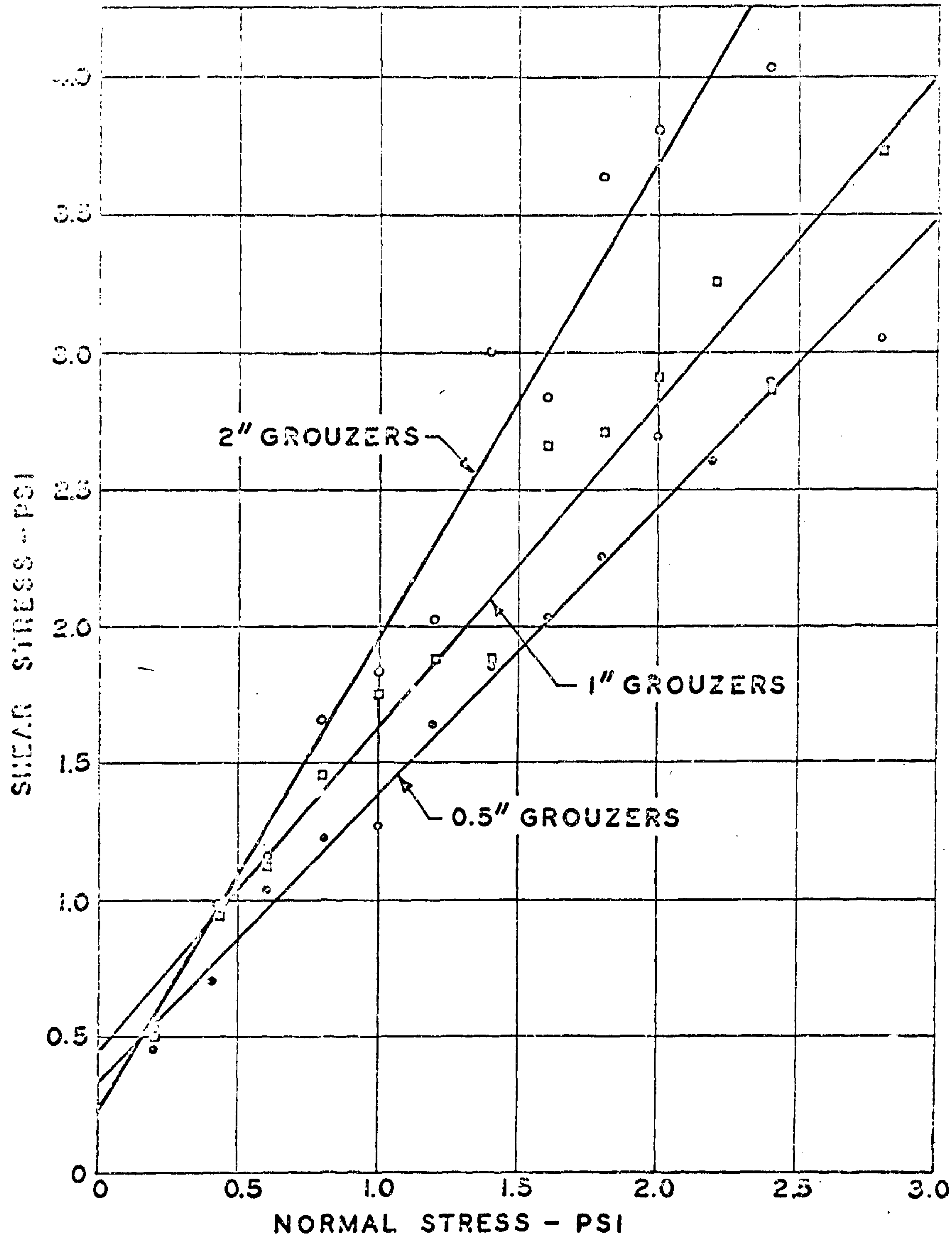

Fig. 28 - Muskeg Shear Tests

As Fig. 28 shows, tan ϕ is greater than unity, or ϕ is greater than 45°, which is typical of all muskeg tested in this program. This ratio of horizontal unit force to vertical unit load is therefore much greater than for mineral soils, and this would indicate that a much greater tractive force could be exerted for a given vehicle weight. This is only partially true, however, because of the much greater sinkage usually experienced in muskeg, as normal load increases. The greater sinkage experienced with high unit normal loads increases the work of compaction of a vehicle, which compensates in part for the higher shear stress that may be developed. Furthermore, higher unit normal loads cause greater sinkage, which, in turn, causes a tensile stress in the upper mat fibers, as a consequence of the deformation or stretching of the mat. Shear loads, under high normal loads, therefore, result in tensile stresses in the mat fibers, not only from tearing of the mat, but also from the stretching action. This latter combined effect closely relates to the effect of a tracked vehicle travelling on the muskeg.

It would appear that a compromise must be made in the design of tracks for muskeg vehicles. Small track areas would produce greater normal unit loads, making possible the development of greater shear strength in the muskeg mat. But, on the other hand, this would also allow greater sinkage, with an increase in tensile

stress in the mat fibers, as well as an increase in the compaction work which the vehicle must overcome.

But then, a very large track area is not good either, since this would not develop as much shear strength in the less compressed mat.

Grouzer design also has considerable effect on the shear stress— normal stress relationship, as shown in Fig. 28. Increasing the depth of the grouzers from 0.5 inches to 1.0 and to 2.0 inches increased the shear stress considerably. From this, one might conclude that for maximum tractive effort muskeg vehicles should be designed with deep grouzers. This conclusion, however, does not take into consideration the damaging effect of aggressive grouzers on the mat. The effect would be of greatest importance where repeated passes are to be made over the same route.

Optimum grouzer depth further depends on vehicle power. In an underpowered vehicle, engine speed drops off before significant track slippage occurs (30-40 per cent). In this case, nothing would be gained by using larger grouzers on muskeg. On the other hand, with adequate engine power a significant increase in drawbar effort can be realized with deeper, more aggressive grouzers.

TENSIOMETER

The grouser action of a track-laying vehicle on muskeg mat is closely approximated by the tensiometer.

The force required to push apart the tines of the tensiometer results from four areas of resistance in the mat. The fibers of the mat directly between the two sets of tines are subject to tension. At the same time, the fibers from the side and bottom of the test area are also subjected to tension. The fourth area of resistance is the mat behind the sets of tines, which is subjected to compression.

An attempt was made to determine the contribution of several of these areas of resistance. A chain saw was used to make a cross cut between the two rows of tines to a depth of about 12 inches. Figure 30 shows that the effect was a very considerable reduction in load, particularly at low displacement.

When saw cuts were made just adjacent to the tines, parallel to the direction of the applied force, no reduction in force was noted for the first 1½ to 2 inches of displacement, indicating that the side fibers did not carry any of the initial load, but were put under tension only after two or more inches of displacement. At about 5 inches of displacement, the parallel cuts seem to have a greater effect on reducing the load, than the cross cut.

It appears that the fibers in direct tension between the sets of tines are the first to be stressed and to fail. As deformation increases, a larger portion of the load is carried by the side fibers, and probably the bottom fibers.

By cutting out plugs of mat behind the tines, an indication of the load carried by compression of the mat behind the tines was observed. As shown in Fig. 29, this amounts to about 10 per cent of the total load, but at larger displacements only.

Previous plate tests carried to mat failure, have indicated that the upper living-fiber portion of the mat provides for the major portion of muskeg resistance to vehicle weight. The tensiometer, as designed, can be used to obtain a quantitative measure of the strength of the top 3, 6, or 9 inches. Figure 30 shows a comparison of mats in the Skanee area, with as much as 50 per cent difference in strength at three inches deflection, for the same type of surface cover (F cover). The lower strength of moss (FI cover) over grass (F cover) is shown in Fig. 31.

The tensiometer measures the tensile strength of the mat at essentially zero normal load, since the instrument weighs only 35 pounds. It is possible that compaction could make considerable difference in the strength of mats. A loose upper mat, which may have a low tensiometer reading, might experience a very con-

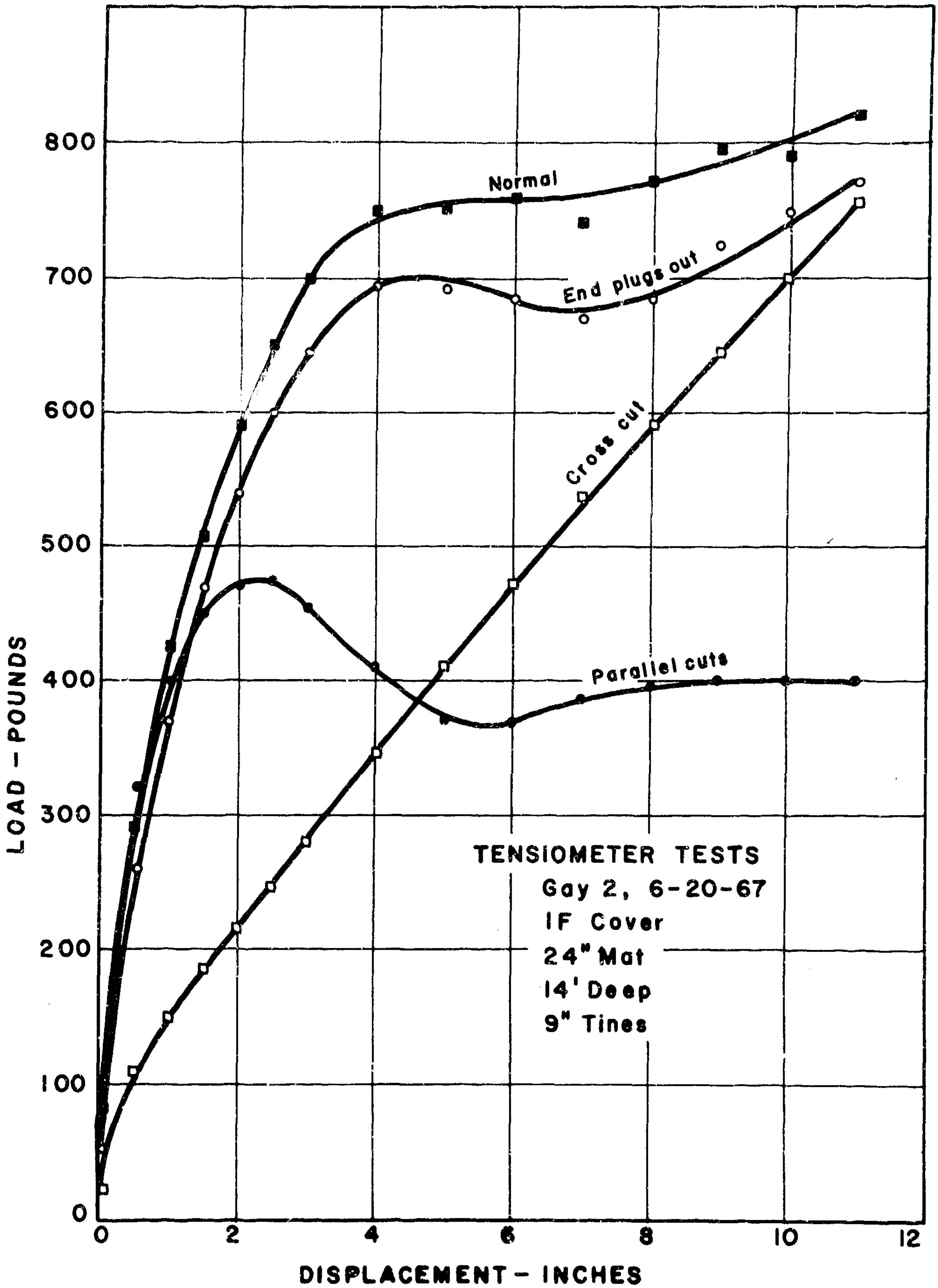

Fig. 29 - Tensiometer Tests

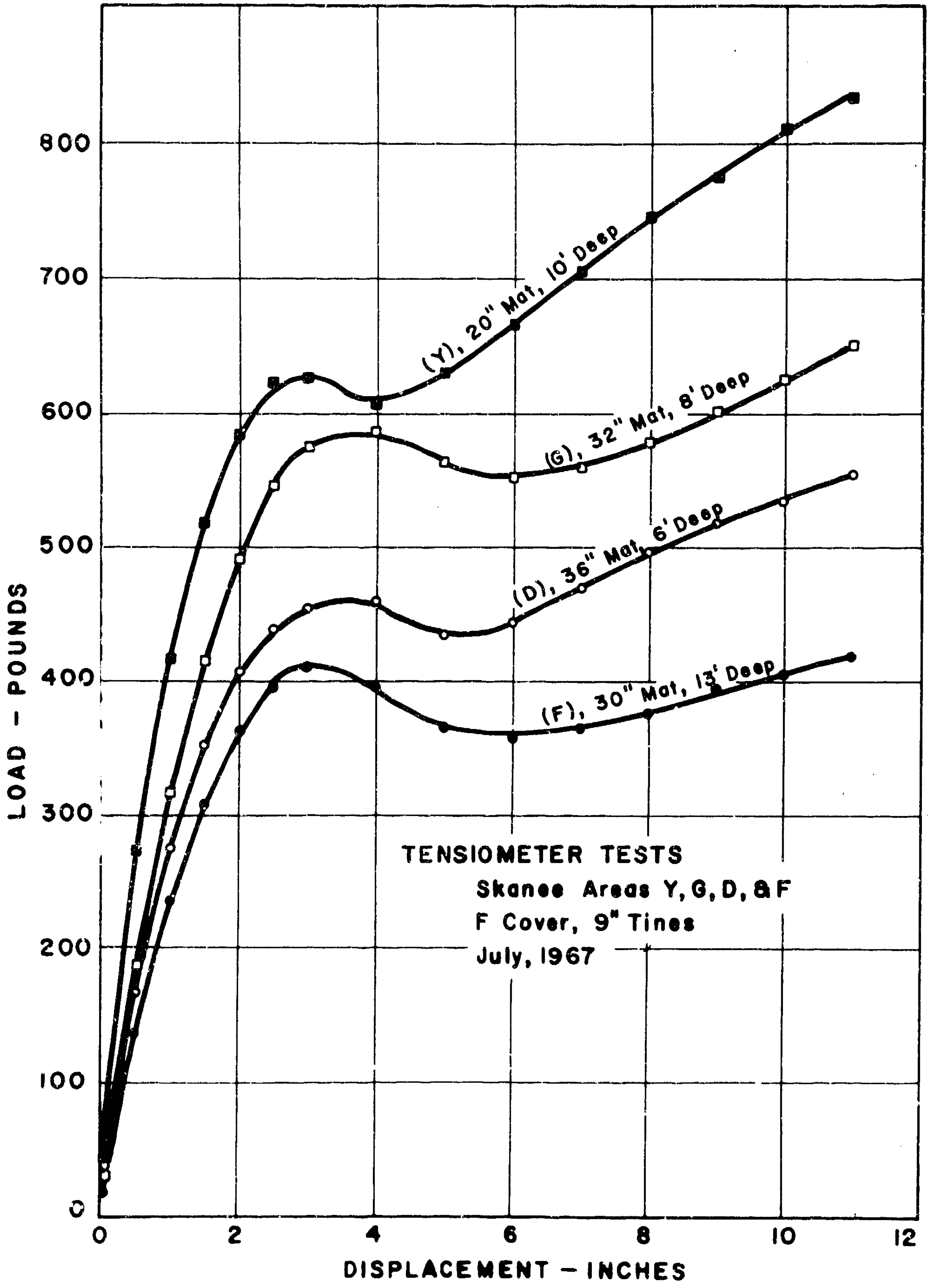

Fig. 30 - Tensiometer Tests, Locations Y, G, D & F

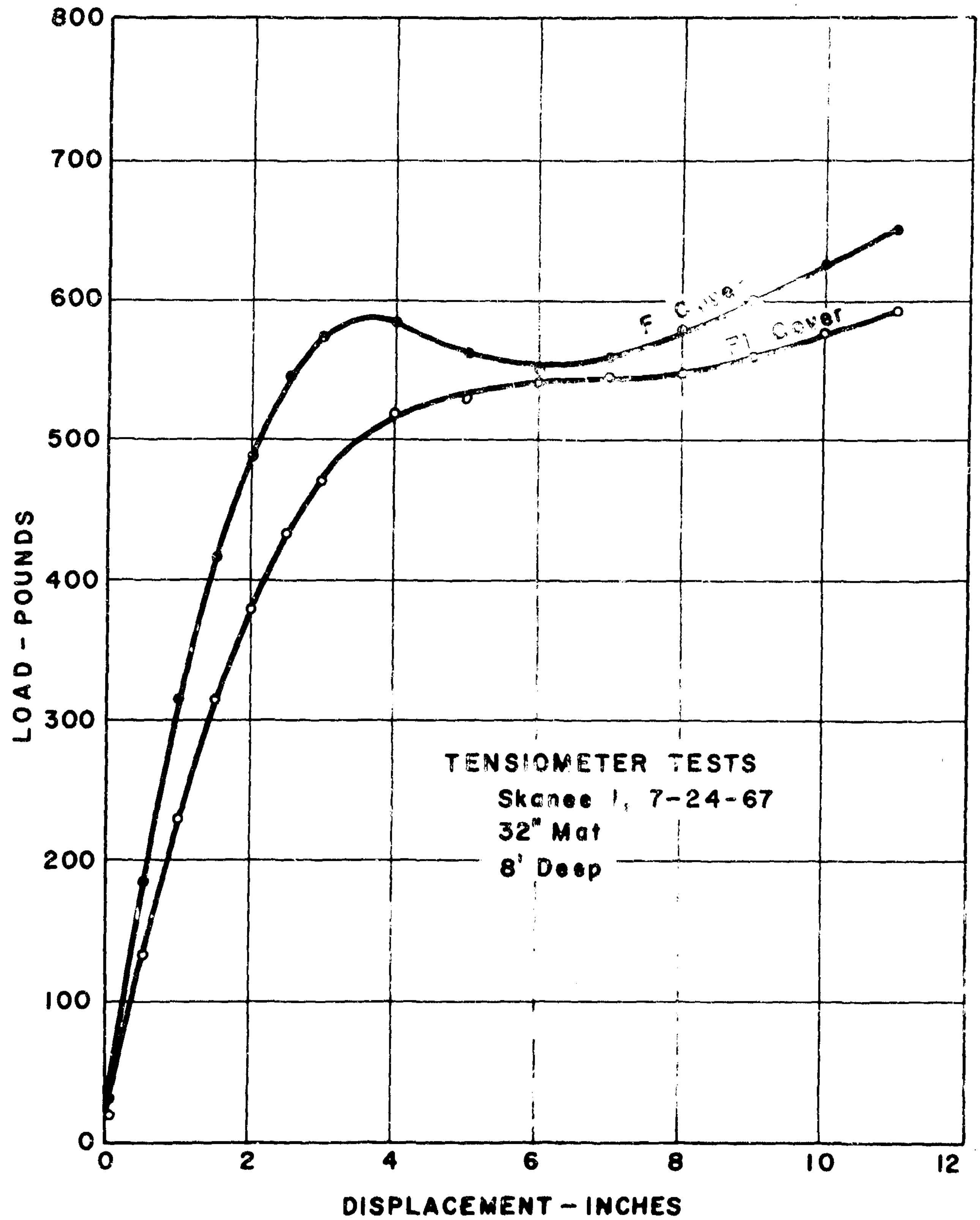

Fig. 31 - Tensiometer Tests, Moss Cover

siderable increase in strength as the result of a normal load, and could surpass the strength of a denser mat. In other words, mat "F" in Fig. 30 could surpass mat "Y" at, say, 3 psi normal load. However, in doing so a vehicle would experience a much larger sinkage and, consequently, a higher compaction resistance.

Tensiometer tests were made with tines set at 3, 6, and 9-inch lengths, as shown by a typical plot in Fig. 32. The strength of the mat increases rapidly with depth, levels off, and then decreases as the bottom of the mat is approached. The strength of the top 3-inch layer is about one-half the strength of the 3 to 6-inch layer or the 6 to 9-inch layer. This is based on the tensiometer load in pounds. Based on the load per unit of area subjected to tension, however, the stress in the upper 3-inch layer is about equal to that in the 3 to 6-inch layer, and almost twice the stress in the 6 to 9-inch layer. This is shown in Fig. 33. It must be kept in mind that, in going from 3 to 6-inch tines, the total tension area is increased by only 50 per cent, since the bottom area remains the same in each case. Similarly, in lengthening the tines from 6 to 9 inches only a 33 per cent increase in area is realized.

A comparison of tensiometer data with plate-sinkage data from the same area shows that for any particular mat cover there is a direct correlation. A mat that shows a high resistance to plate

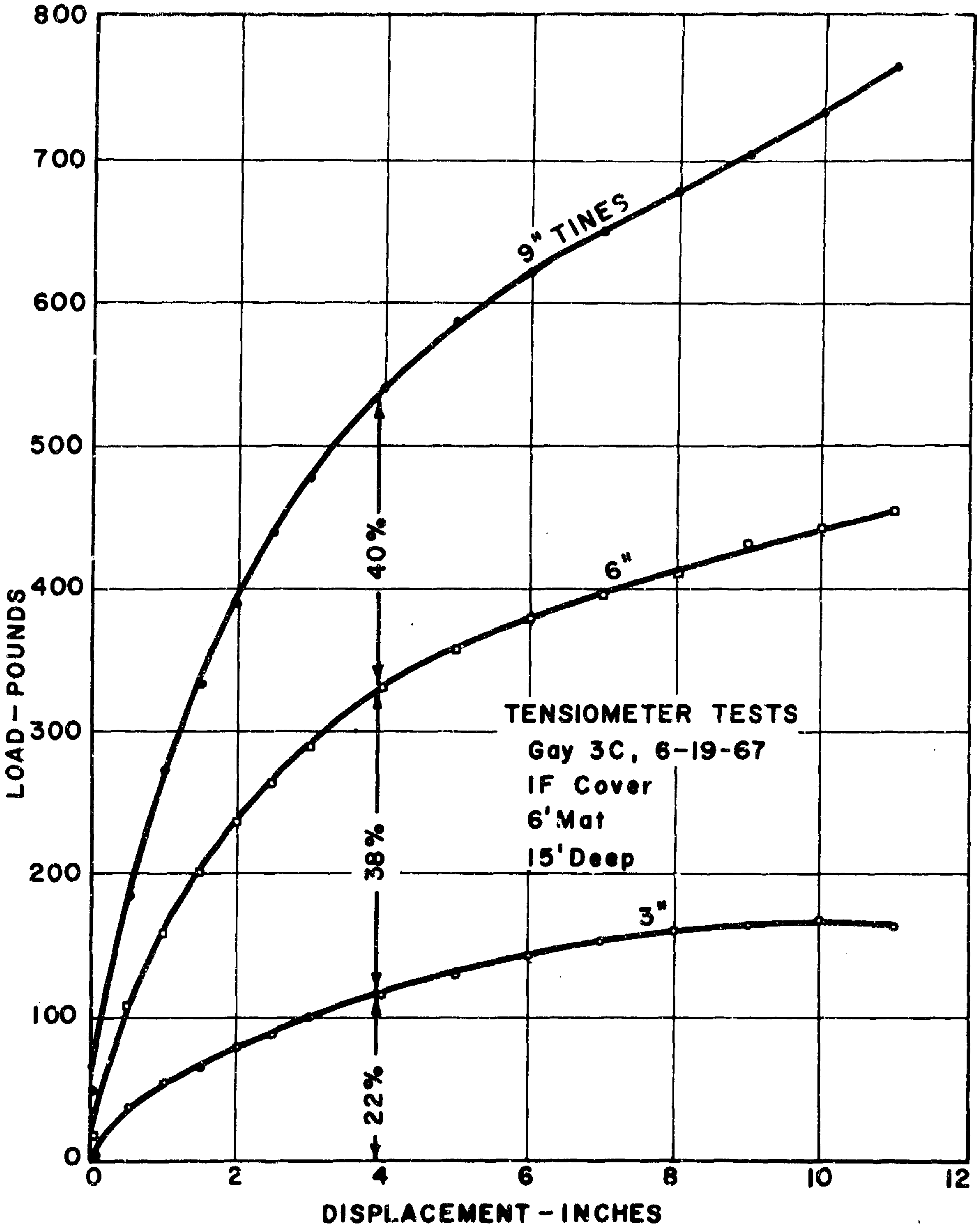

Fig. 32 - Tensiometer Tests - Variable Length Tines

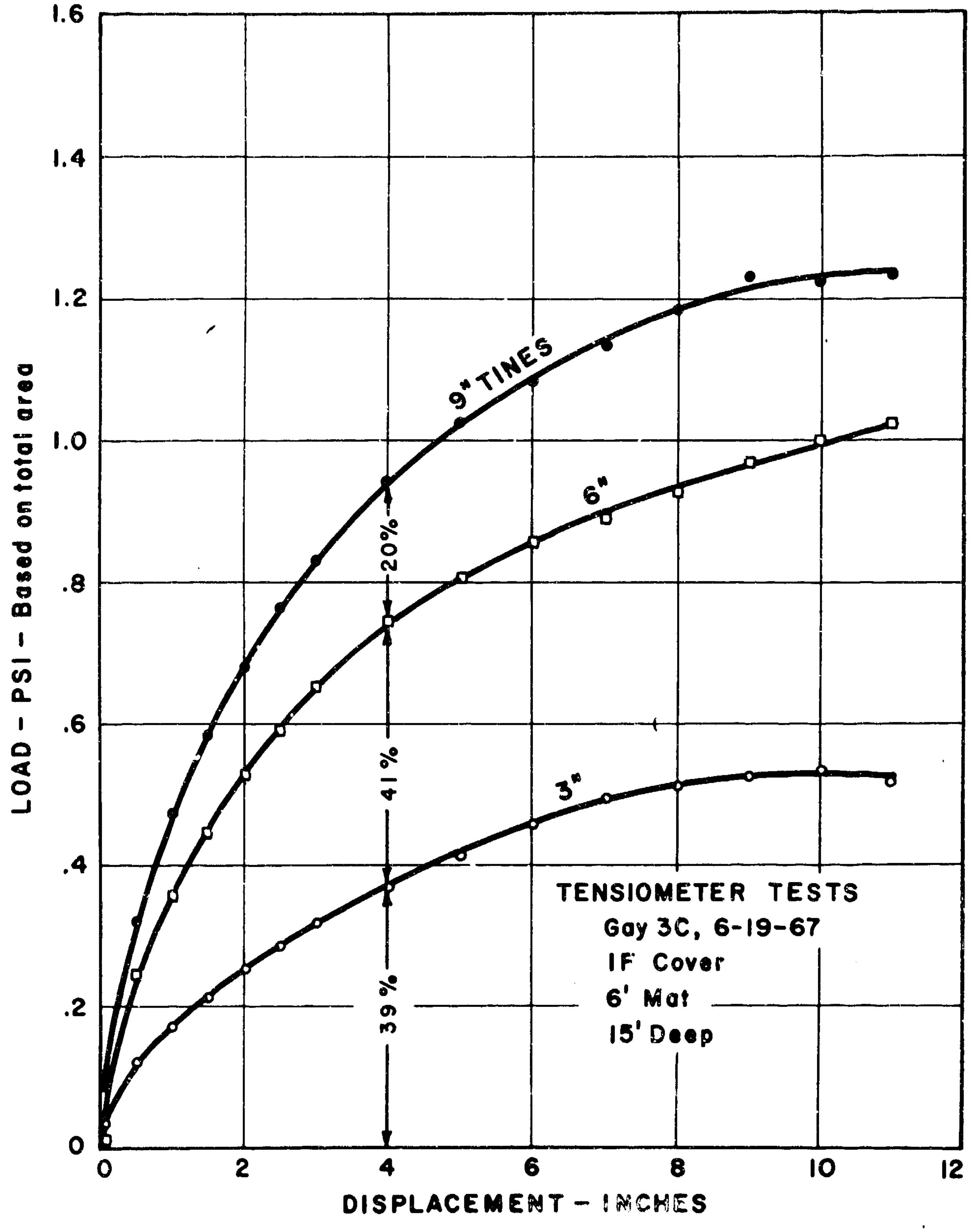

Fig. 33 - Tensiometer Tests - Variable Length Tines

penetration demonstrates a high tensiometer load as well. This is to be expected since, as explained earlier, plate penetration results in tensile stresses in the upper mat. The correlation is not as good when greatly different muskegs are compared, since resistance to plate penetration is a function of more than just upper-mat fiber strength.

CONE PENETROMETER

The cone penetrometer has been widely used as a device for evaluating the strength of soil, and attempts have been made to use it on muskeg. The Waterways Experiment Station (WES) in Vicksburg, Mississippi, has used a small 30 degree cone in an attempt to relate cone penetration resistance to vehicle mobility. A vehicle cone index (VCI) was devised, based upon the cone resistance value required to allow 50 consecutive vehicle passes without immobilization.

A VCI based on 50 passes in the same track is arbitrary and could have been based on 10 or 5 or even 1 pass. In view of the wide open nature of most muskeg areas, multiple passes over the same track are not necessary or desirable. The crossing of muskeg areas is generally an expedient or emergency measure rather than a repeated operation, and the important question is not if a given vehicle will cross 50 times in the

same track, but can it cross even once.

The cone penetrometer is an easily portable device for evaluating soils, and, as such, deserves consideration as an evaluation tool. As part of the field work, cone penetrometer tests were made with WES 30^{o} cones of both 1/2 square-inch and 1 square-inch base areas. A modification made to expedite the cone tests was the use of a sensitive strain-gage load cell in place of the proving ring and dial indicator, and a potentiometric displacement transducer in place of visual indications of depth. The output of the two transducers produced a load versus sinkage plot on an X-Y recorder as shown in Fig. 34.

The ten tests plotted in Fig. 34, all taken within a four square-yard area, show the typical non-homogenity of muskeg. Because each cone test involves such a small sample of the soil, a very large number of tests must be made to obtain a meaningful average.

Although the cone penetration resistance does vary with mat strength as measured by plate, shear, and tensiometer tests, it is also very sensitive to mat density. Figure 35 shows the variation in cone penetrometer resistance for the same four locations on the Skanee muskeg, for which tensiometer data is illustrated in Fig. 30. Each plot is the average

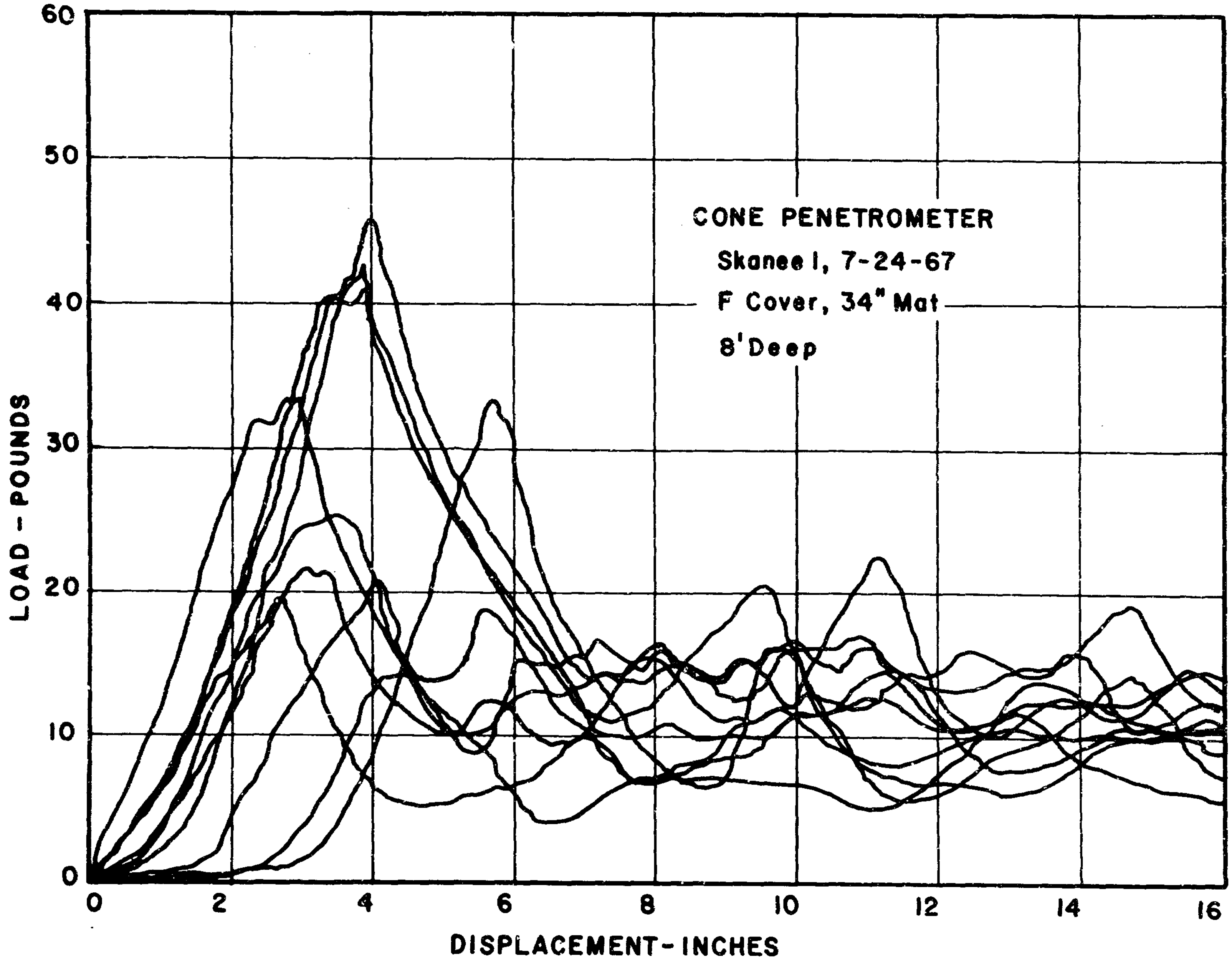

Fig. 34 - Cone Penetrometer Tests

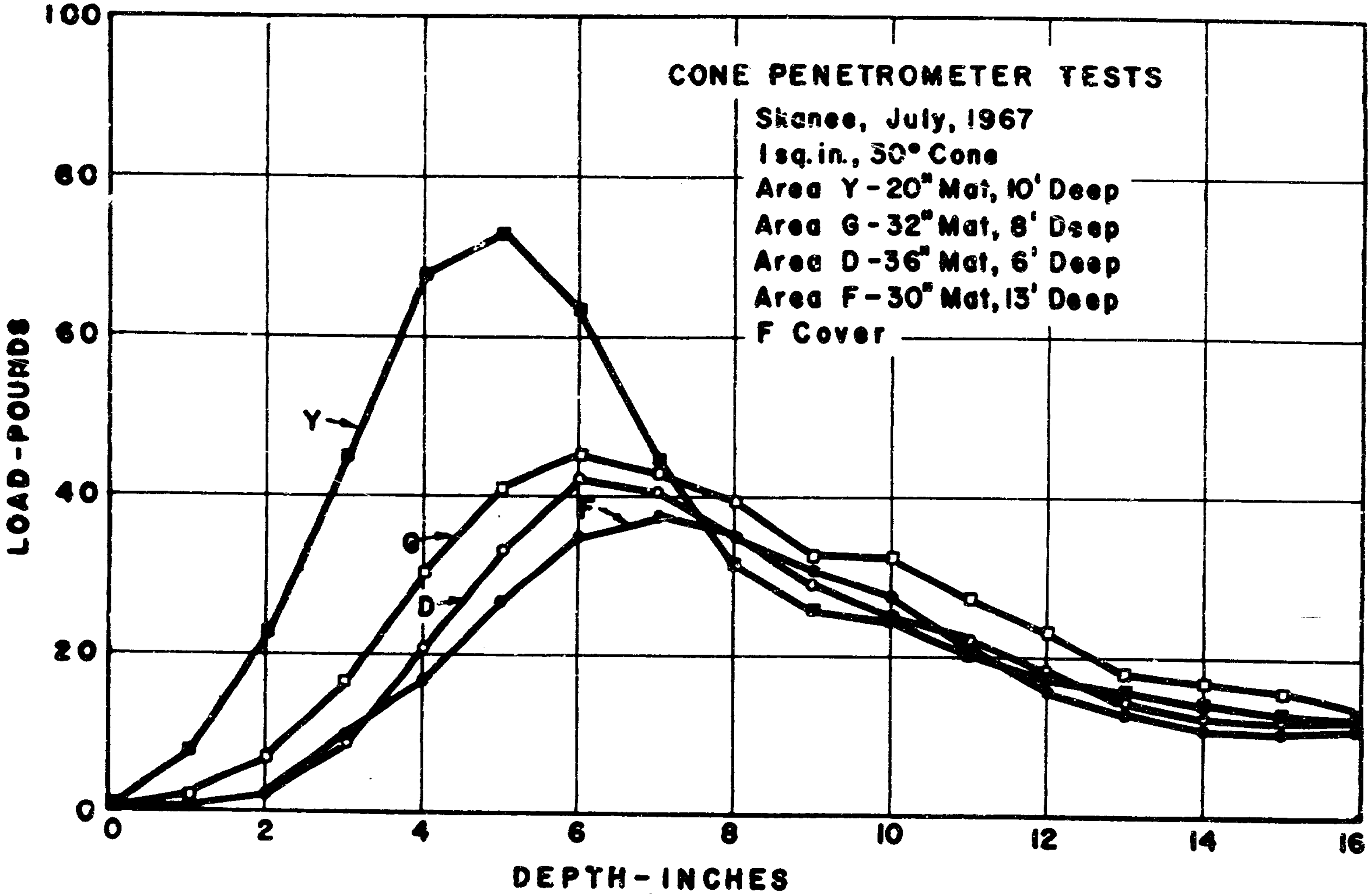

Fig. 35 - Cone Penetrometer Tests, Locations Y, G, D, & F

of 20 cone-tests. The mat in location "Y" shows a considerably greater resistance to the cone penetrometer than the mat in the other three locations. Its unusually high density offered much greater resistance to the cone, but did not exhibit the same degree of increased tension strength when tested with the tensiometer.

The 1/2 square-inch and 1 square-inch cones were used in muskeg, for comparison. It is apparent from Figs. 36 and 37 that the resistance to the 1 square-inch cone is not twice that of the 1/2 square-inch cone at all depths. The average resistance for the 1/2 square-inch cone down to six-inch penetration in F cover (Fig. 36) was 13.6 pounds, compared to 23.7 pounds for the 1 square-inch cone, or 57 per cent of the 1 square-inch cone resistance. If the values at three-inch penetration are used, however, the relationship is far from two to one. For FI cover, the relationship between the 1/2 square-inch and 1 square-inch cones is far from the expected values, at least at shallow penetrations, Fig. 37.

A further discrepancy between cone penetrometer data and other tests occurred within variation of cover types. For example, cone penetrometer tests indicate greater resistance in FI cover (grass and moss) than in F cover (grass only). This is undoubtedly due to the higher density of the moss. On the other hand, tests such as shear, tensiometer and even actual vehicle

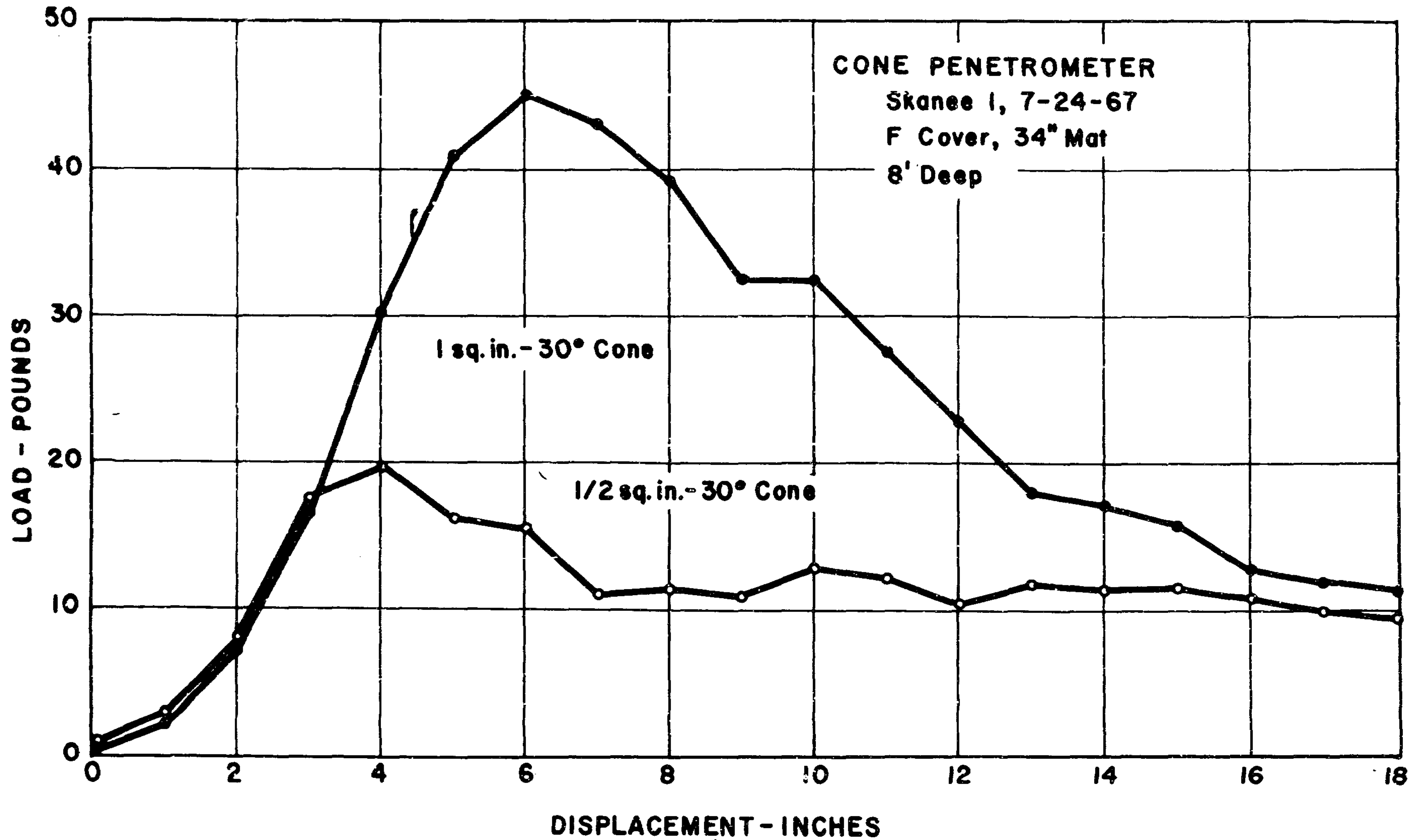

Fig. 36 - Cone Penetrometer, 1/2 vs. 1 sq. in. Cones

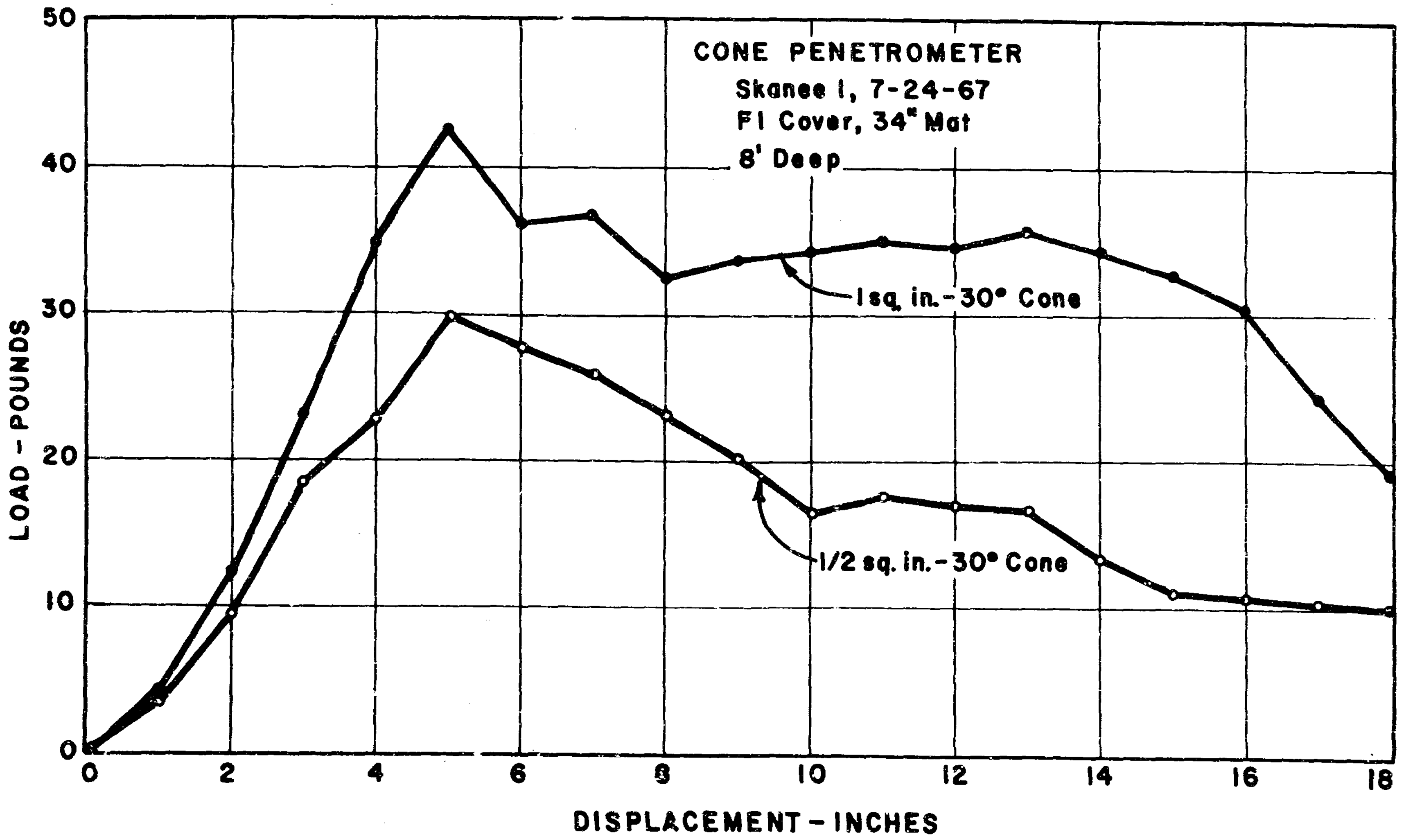

Fig. 37 - Cone Penetrometer, 1/2 vs. 1 sq. in. Cones

drawbar tests showed the opposite to be true, greater strength for F cover than for FI cover. Figure 31 shows tensiometer data for various cover types while Fig. 38 shows the cone penetrometer data on the same cover types.

It appears, unfortunately, that the cone penetrometer has limitations as a suitable device for determining the load carrying characteristic for muskeg.

DRAWBAR PREDICTION

Early in the project a decision was made to base an analytical prediction method for vehicle mobility in muskeg on the Land Locomotion Division (USATACOM) methodology for determining drawbar pull.[1,2] Plate sinkage and shear tests were made in muskeg areas to give the required soil parameters for predicting drawbar pull.

Plate sinkage tests were made with several sizes of large rectangular plates to obtain values for the following soil parameters: moduli of sinkage, k_c and k_ϕ, and sinkage exponent, n, using the equation,

$$p = \left(\frac{k_c}{b} + k_\phi \right) z^n$$

[1] Report No. RR 46, LL 68, Over-Snow Vehicle Performance Studies by Wm. L. Harrison and Tibor Czako, November, 1961, USATACOM, Centerline, Michigan.

[2] Report No. RR 47, An Analysis of the Drawbar Pull versus Slip Relationship for Track Laying Vehicles, by Z. Janosi and B. Hanamoto, November, 1961, USATACOM, Centerline, Michigan.

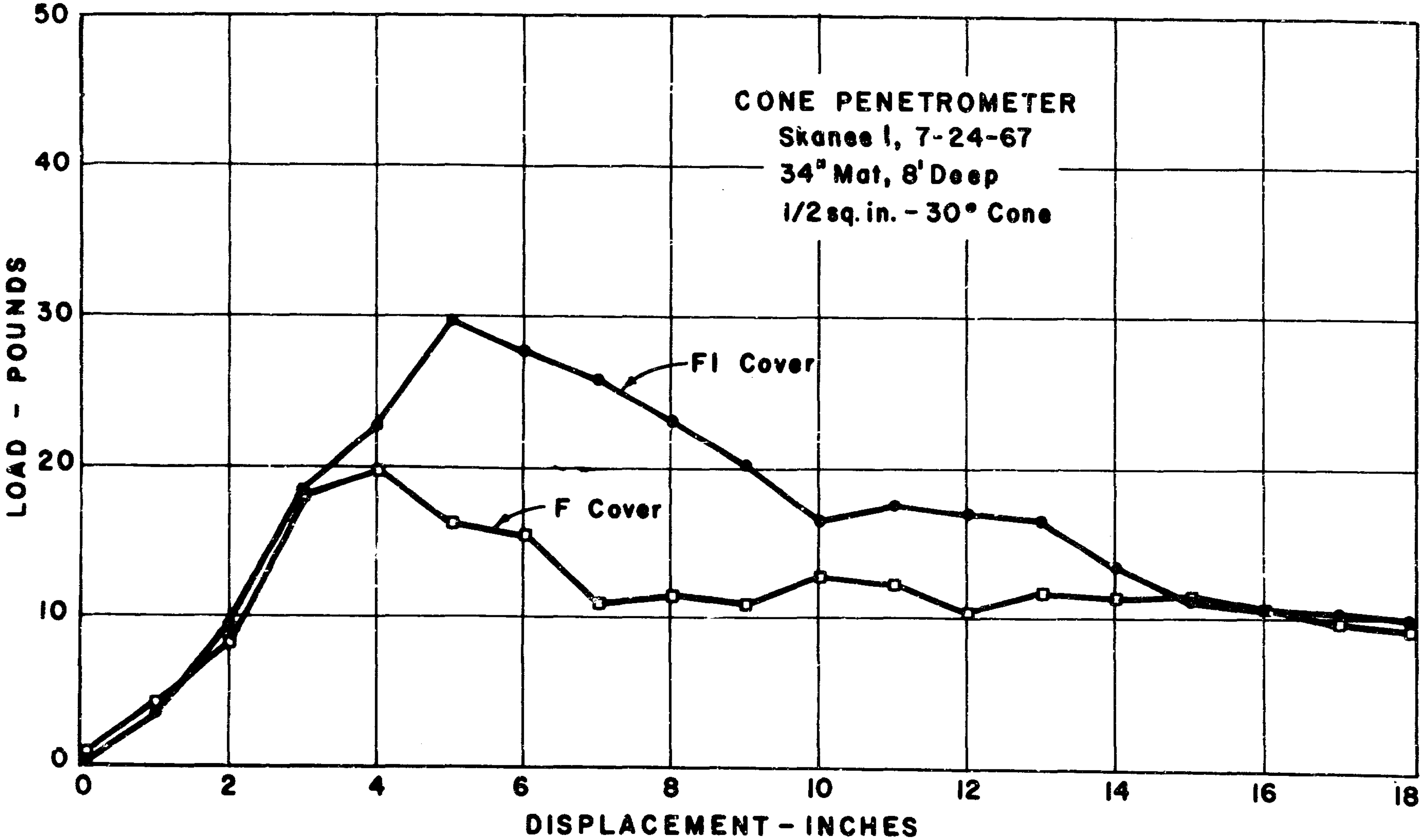

Fig. 38 - Cone Penetrometer, Effect of Cover Type

where p is the ground pressure in psi, b is the width of the loading element in inches, and Z is the sinkage in inches.

Similarly, shear tests at various normal loads were made to obtain values for: angle of friction, ϕ, and cohesion c, using Coulomb's Equation,

$$S_s = c + p \tan \phi$$

where S_s is the shear stress in psi.

Since a tracked vehicle exerts a variable ground pressure along the length of the track, it is necessary to construct a series of shear stress versus shear deformation curves for a number of points along the track, using the soil test results. On these curves, then, connecting points which represent the same percentage of slip for each track-length value, and graphically integrating the area under this line, a value for the gross tractive effort of the vehicle, per inch of track width, is determined for a particular value of slip. Repeating this procedure for a number of slip values makes it possible to construct a tractive effort versus per cent slip curve for the vehicle.

The gross tractive effort, however, must be reduced by the amount of vehicle tractive effort used for compaction of the soil resulting from sinkage. This compaction effort, R_C, may be calculated by using the previously determined soil values.

To check the application of the Land Locomotion Division prediction procedure to muskeg, a series of drawbar tests were performed with an M29C Weasel in the Skanee muskeg. Figure 39 shows the predicted analytical curve of tractive effort versus per cent slip.

A maximum net tractive effort of 7,560 pound is predicted at 67 per cent slip, which gives a drawbar pull to weight ratio of 1.27. A series of ten drawbar tests at various engine speeds, in low gear, low range were conducted. The range of results are plotted as broken lines. The maximum sustained tractive effort obtained averaged 5,200 pounds or a DP/W of 0.87.

There is good agreement between the experimental results and the analytical prediction up to slip values of about 25 per cent. At slip over 25 per cent, the tractive effort diminished rapidly due to increased sinkage resulting from tearing of the muskeg mat. Track sinkage at the rear varied from 15 to 18 inches at points of maximum drawbar, resulting in a bottoming of the Weasel and a consequent reduction in tractive effort. Very few reliable readings could be obtained at more than 30 per cent slip.

Evaluation of this prediction procedure, without the limitation imposed by bottoming, was later attempted in firmer muskeg areas at Skanee and Gay. Figure 40 shows a plot of the analytical drawbar predictions and the limits of the experimental results.

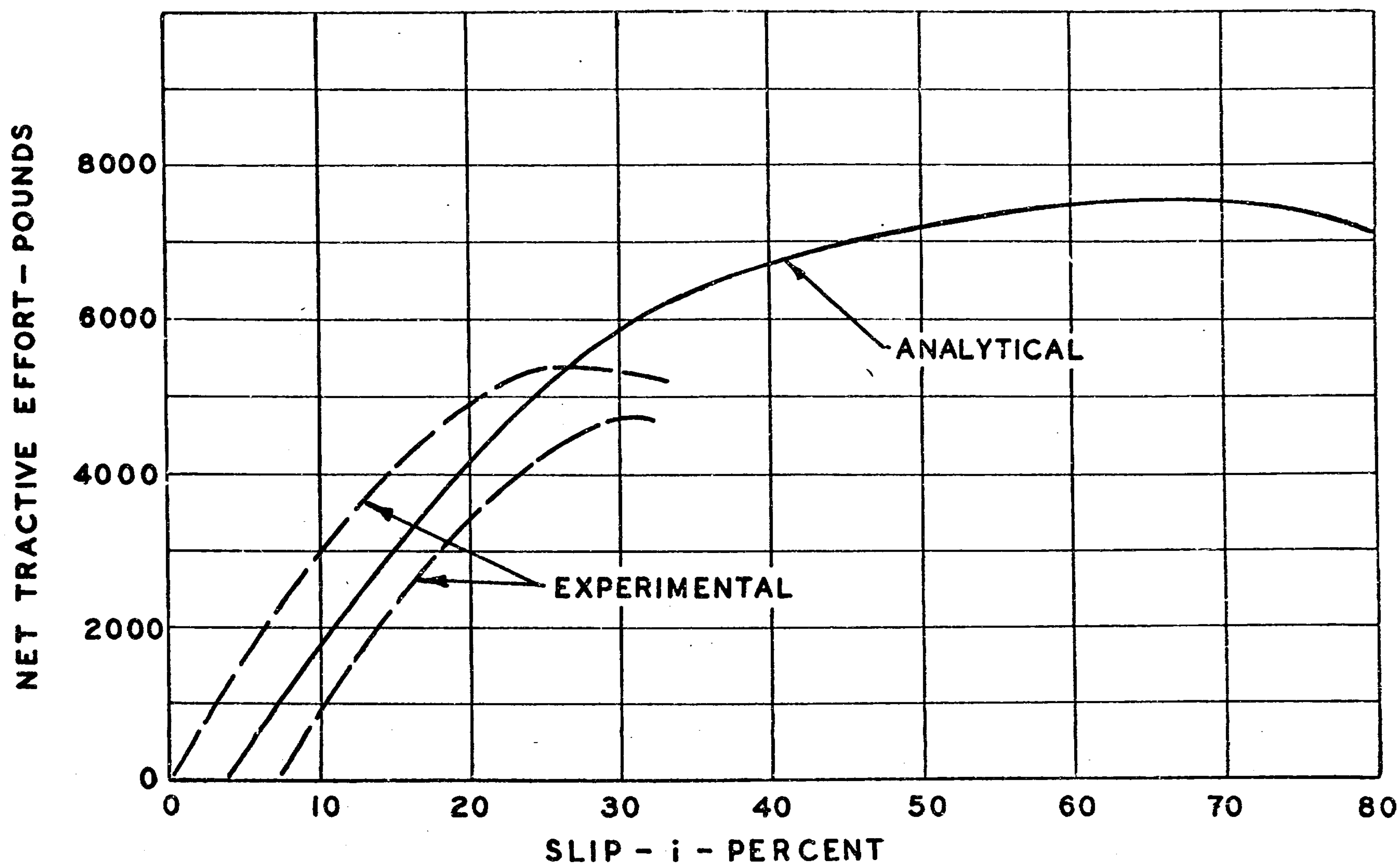

Fig. 39 - Tractive Effort vs. Slip of M29C in Weak Muskeg

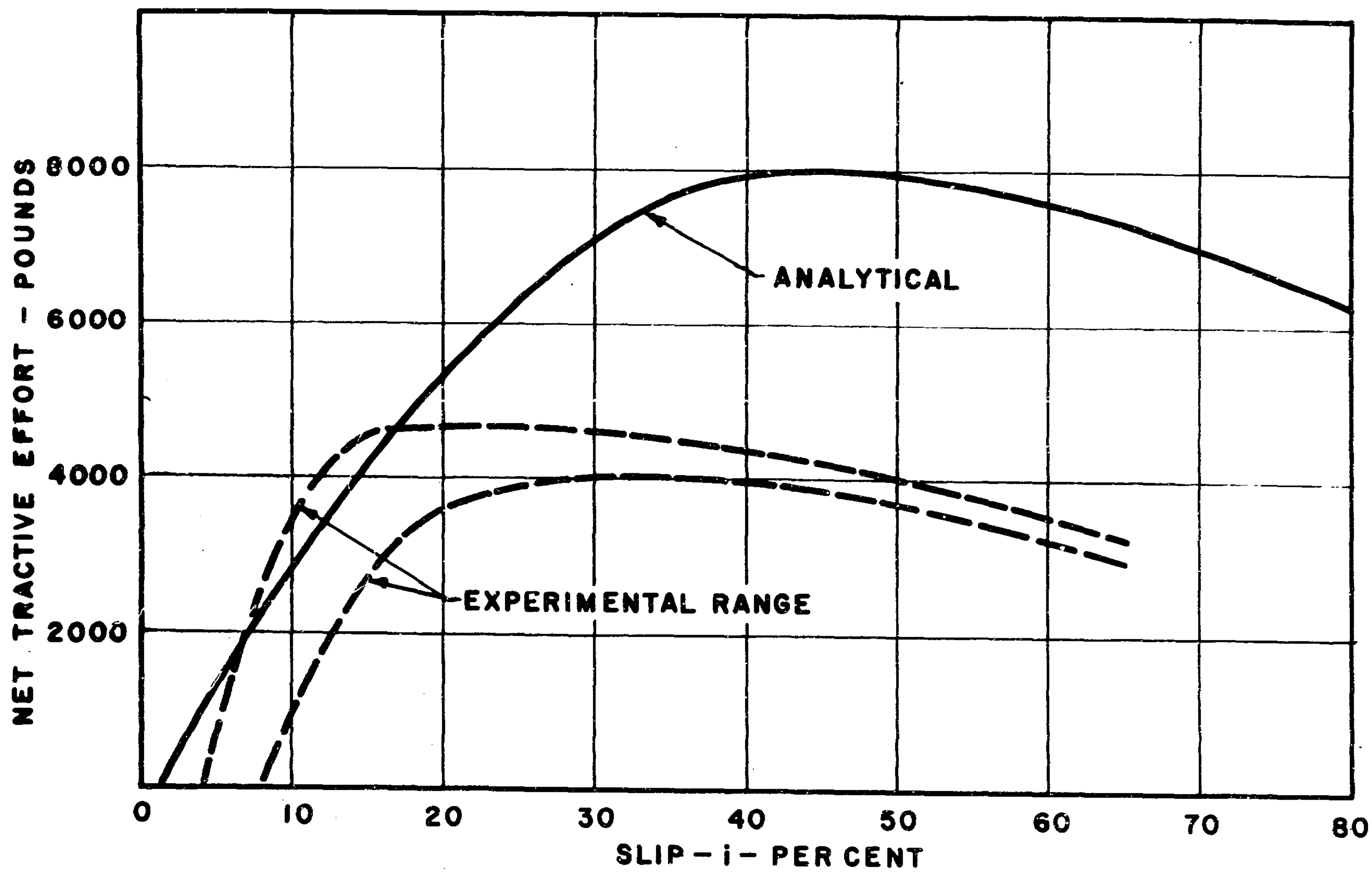

Fig. 40 - Tractive Effort vs. Slip of M29C in Firm Muskeg

The experimental values again fell far short of the maximum dicted figure, but for a different reason. Excessive sinkage not a problem, since it rarely exceeded 10 inches at the rear the Weasel. Engine torque, however, seemed to limit the drawbar pull and the engine speed dropped off almost to stall when the load was increased over 4,000 pounds. It appears that in these tests the strength of the muskeg soil was not the limiting factor for this particular vehicle. Net drawbar effort was limited to 75 to 85 per cent of gross vehicle weight either by excessive sinkage or lack of sufficient engine torque.

CONCLUSIONS

Vehicle mobility in muskeg is a function of many variables. The unit pressure on the track has an important effect on both the vehicle ability to traverse the muskeg and its net drawbar pull. If the loading is very light the vehicle will traverse weak muskeg readily, but will not be able to pull much load. A certain amount of mat compaction is desirable since the shear strength of muskeg increases very rapidly with normal load, which, in turn, affects drawbar pull.

A large perimeter-to-area ratio is desirable, since mat failure occurs at the perimeter of a plate or track due to tensile failure of the mat fibers.

The depth of the track grousers also play a role in the drawbar pull a vehicle can exert. Deep grousers increase the maximum drawbar pull, but also damage the mat to a greater extent, thus reducing the number of repeated passes that can be made.

Several properties of the muskeg itself affect the mobility of a vehicle. The load-sinkage relationship not only determines whether a vehicle can safely travel over the muskeg, but also determines the compaction resistance a vehicle must overcome. This is a function of cover type, thickness, and density of the mat, as well as the nature of the peat underneath.

The "shear" strength of the mat varies with mat composition, or cover type, as well as with normal load. A shearing force does not produce failure in the same fashion as in an organic soil, but rather a tensile failure in the mat fibers. It is the tensile strength, therefore, that governs the shear load a mat can carry. The tensile strength of the mat also governs the load-sinkage relationship, since a vertical loading of the mat produces tensile stresses in the fibers making up the surface layer of the mat.

The density of the mat and peat also has an effect on the load-sinkage relationship. A firm and well consolidated peat, with low water content, will resist deformation at the bottom of the mat, and sinkage will occur primarily by compression of the mat.

In the case of floating mats, over very liquid peat, sinkage is a function of the tensile strength of the mat, its density, and the flow resistance of the displaced peat. A very liquid peat (500-1500 per cent water) exhibits thixotropic flow characteristics, that is, it offers more resistance to flow at low displacement rates than at high rates. The fibrous material, which makes up the solid portion of the peat, is randomly oriented in its natural state or at low flow rates, but aligns itself in the direction of flow at high rates, with a reduction in flow resistance at the higher rates of loading. After passage of a vehicle the mat recovers slowly, to near its original position. A corresponding return flow of peat, however, does not take place. The fibrous portion of the peat seems to remain in its displaced position. This phenomena has been verified by taking a series of large-sized cone penetrometer tests on the peat before and after plate sinkage tests. An increase was noted in peat resistance immediately adjacent to the plate test position or track passage area and a decrease in peat resistance directly under the plate test area.

It would appear that repeated passes over floating mat muskeg should not be made in the same track, but just adjacent to the previous track. This procedure would take advantage of the consolidation of the peat produced by the previous pass.

Of the various characteristics of muskeg terrain, the tensile strength of the top 6 to 9 inches of living mat fiber seems to be the most important single property affecting vehicle mobility. The tensile strength of the upper mat not only determines the shear load that may be resisted, but also the sinkage caused by a normal load.

It would appear that a vehicle mobility index could be devised, based upon tensile test data on the upper mat, using a device such as the tensiometer described in this report. This data could be correlated with go and no-go mobility tests with various vehicles, either based on single or multiple-pass performance in various types of muskeg.

With such a tensiometer index for each vehicle, a portable tensiometer could then be used to survey unknown muskeg to determine whether a vehicle could make a single or multiple traverse over it.

APPENDIX A

MUSKEG AREAS IN MICHIGAN'S UPPER PENINSULA

The following listing represents the muskeg areas that were located during the project, and on which site inspections were made. The location of each site is indicated on the map in Fig. 1, with the primary access routes to each indicated. This list does not necessarily include all the muskeg areas in the Upper Peninsula, but represents the most prominent ones, and the most promising ones for the project. Some areas were not used, even though quite sizeable, because of their remoteness from project headquarters, or because they were similar in character to areas which were closer and more easily accessible.

1. Lake Upson Area (Keweenaw County)
   Section 36, T59N, R30W
   40 Acres, Radforth Classification DF and FD
   Depth to 20 feet

2. Lac La Belle Area (Keweenaw County)
   Section 34, T58N, R29W
   40 Acres, Radforth Classification FEB
   Depth 4 to 5 feet

3. Lac La Belle Area (Keweenaw County)
   Section 3, T57N, R29W
   20 Acres, Radforth Classification FI
   Depth to 4 feet

4. Gay Area (Keweenaw County)
Section 24, T56N, R31W
Section 19, T56N, R30W
280 Acres, Radforth Classification F, FI, IF, FIE, and EIF
Depth 6 to 13 feet

5. Highway M35 Area (Baraga County)
Sections 5 and 6, T50N, R34W
Section 35, T51N, R34W
250 Acres, Radforth Classification EFI
Depth to 9 feet

6. Pequaming Area (Baraga County)
Section 4, T51N, R32W
Sections 32 and 33, T52N, R32W
400 Acres, Radforth Classification F, FI, and IF
Depth 3 to 9 feet

7. Skanee Area (Baraga County)
Section 13, T52N, R31W
200 Acres, Radforth Classification F, FI, and FIE
Depth 3 to 11 feet

8. Park Siding Area (Baraga County)
Sections 28 and 33, T47N, R33W
400 Acres, Radforth Classification EI, IF, and EIF
Depth 2 to 6 feet

9. Dead Stream Area (Iron & Houghton Counties)
Section 33, T47N, R35W
Section 4, T46N, R35W
25 Acres, Radforth Classification FEI
Depth to 13 feet

10. Hope Lake Area (Iron County)
Sections 14 and 23, T43N, R32W
160 Acres, Radforth Classification EI
Depth to 9 feet

11. Channing Area (Dickinson County)
Section 6, T43N, R30W
Sections 31 and 32, T44N, R30W
200 Acres, Radforth Classification EF
Depth to 5 feet

12. Seven Mile Marsh Area (Delta & Menominee Counties)
Sections 24 and 25, T37N, R25W
Sections 19 and 30, T37N, R24W
400 Acres, Radforth Classification EI
Depth to 12 feet

13. Nawakwa Lake Area (Alger County)
Sections 19 and 30, T48N, R13W
120 Acres, Radforth Classification IF and IE
Depth to 32 feet

14. Seney Area (Luce County)
Sections 31, 32, and 33
1600 Acres, Radforth Classification EI, FI, and FIE
Depth 4 to 8 feet

15. Wanamaker Lake Area (Luce County)
Sections 27 and 28, T46N, R12W
450 Acres, Radforth Classification DFI
Depth 4 to 5 feet

16. Quinlan Lake Area (Luce County)
Section 34, T47N, R12W
110 Acres, Radforth Classification EF and FIE
Depth to 30 feet

17. Sleeper Lake Area (Luce County)
Sections 3, 4, 5, 9, and 10, T47N, R10W
Sections 13, 14, 15, 22, 23, 27, 28, 32, 33, and 34
T48N, R10W
Nine Square Miles (approximately)
Radforth Classification FE, FI, IF, FIE and IFE
Depth 2 to 13 feet, but fairly constant in a particular area